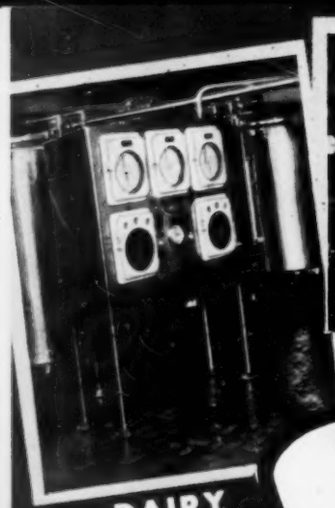
Instruments

THE MAGAZINE OF *Measurement and Control*

Vol. XIII
SEPT. 1940
No. 9



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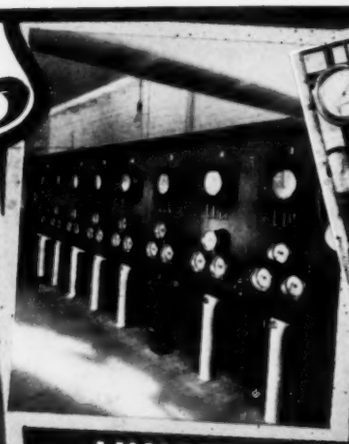

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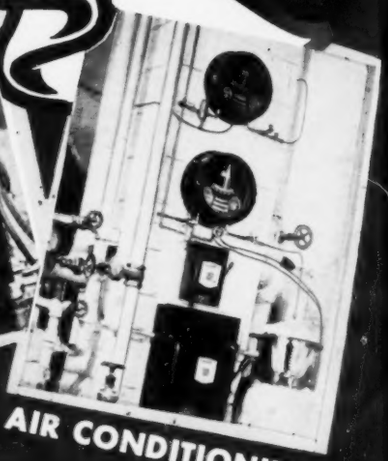

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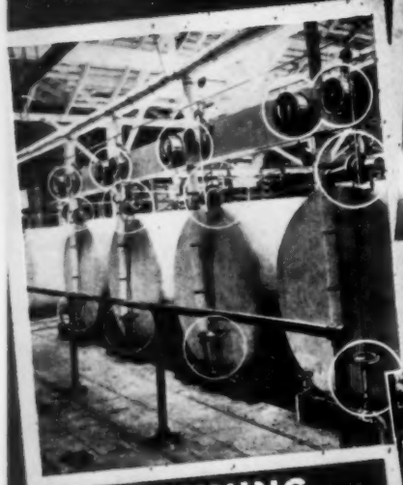

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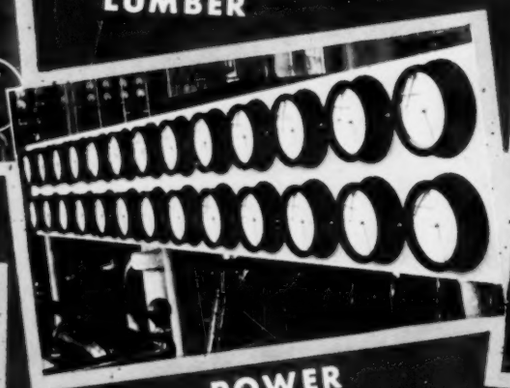

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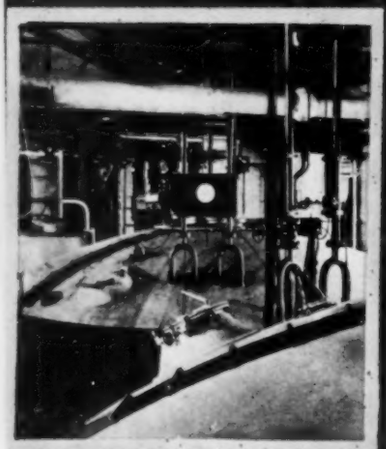

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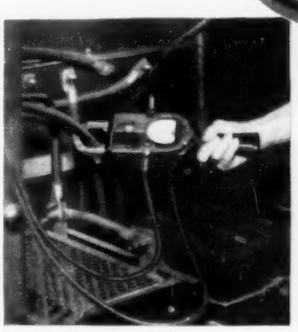

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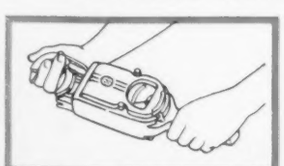
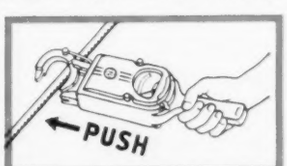
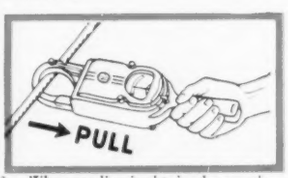


1. Pull "hook" slightly and it snaps open. No trigger to pinch fingers.



2. Place open "hook" around conductor; a slight push on handle snaps it shut, and instrument is ready for reading.



3. When reading is obtained, a gentle pull on handle opens dovetail joint and releases conductor. No trigger connected to live parts.

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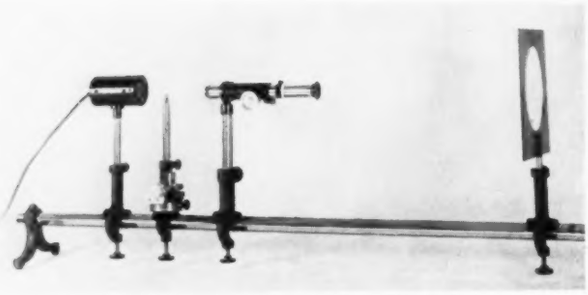

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Instruments
THE MAGAZINE OF MEASUREMENT and CONTROL

Vol. XIII SEPTEMBER 1940 No. 9

COVER: One of the stations in Cummins Engine Co.'s new testing department
Courtesy The Austin Co., Engineers and Builders
Story on page 271

Temperature Measurement and Control

A NEW BOOK BY
M. F. BEHAR

Introduction and chapters on Industrial Thermometry complete in This Issue

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PUBLISHER'S ANNOUNCEMENT—*This is not merely a new edition of Major Behar's 1932 book "Temperature Measurement and Control" but a complete revision. Coming instalments: Industrial Pyrometry in October, Temperature Control in November and December.* —RICHARD RIMBACH

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Instruments

THE MAGAZINE OF Measurement and Control

M. F. BEHAR, Editor

The Most Important Measurable

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IN industry, temperature is by far the most important, not only of processing conditions but of working conditions and even of storage conditions. While its successful industrial measurement is comparatively recent, its attempted control for the sake of bodily comfort goes back to prehistoric ages, and intelligent observations of its effects as a processing condition were made and handed down by ancient cooks and bakers, spinners and weavers, smelters and smiths, potters and ceramists, and other forerunners of industrial engineers, long before the distinctions between heat and temperature were formulated. Every industry is a temperature industry and every process is a temperature process. There are no exceptions. Take the mining industry and in particular the magnetic separation process, as an extreme example. No exception there: For when a separating plant is erected in the Far North, something has to be done about temperature as a working—if not a processing—condition. The general rule still stands: every process is a temperature process. The only thing suggested by the separating process example is that in that particular case the "one best" temperature is anywhere in the comfort range. In *that* sense, our extreme example does furnish an exception, for the optimum temperature of most industrial processes lies within a narrow range—a few degrees too hot or too cold and production is spoiled. If it were not so you would not be reading this book.

It must be emphasized at the outset that industrial service conditions compel a re-definition of the laboratory meaning of "results." Many a laboratory worker nurses and coddles his instruments, and in effect creates special conditions under which his pets can "do their stuff" to the fourth decimal. Some hard-boiled production men may take another extreme and demand the impossible. The engineer, equipped with knowledge of the principles related to the application and to the instrument, takes a reasonable attitude.

Temperature gradients in many pieces of industrial equipment make it utterly hopeless to expect to measure "the temperature." In large drying compartments the gradient often exceeds 50°F. when the desired temperature is only around 300°F., especially when trays or other obstructions prevent good circulation. The measurement of the temperature of non-incandescent pieces of solid materials inside an oven or other apparatus is also a difficult task. Even in the case of an empty oven—empty but for air or gas—the readings of a thermometer bulb or thermocouple junction will ordinarily be affected by conduction along, and by radiation from and to, the bulb chamber, well, or socket. When the air or gas is in motion, as in a flue or duct, there is no such thing as "the" temperature and what is required for exact and complete knowledge is not a measurement but an investigation—to which statement power-plant and air-conditioning engineers will say amen! But aren't flue gas thermometers in constant use everywhere? Certainly; and their successful use provides an illustration of the engineer's "happy medium" view of temperature measurement and control:

1. Too painstaking scientific methods and the use of delicate non-industrial temperature instruments are unnecessary for the successful routine conduct of processes in industrial plants.

2. Measurements of "the temperature" will be dependable and significant if properly-selected instruments are properly installed, with special care that their bulbs or couples be placed where the temperature is representative. Actual immersion is not always necessary: in the operation of open-hearth furnaces, for example, optical or radiation pyrometers are most frequently sighted on the inner face of the roof—not only because of the difficulties of measuring the temperature of liquid steel but because of the economic factor.

3. Automatic temperature control can generally be realized if the primary or sensitive element be sufficiently responsive to temperature variations, the other elements adequate for their respective functions, and the whole properly installed on equipment that lends itself to control.

After all, these statements are self-evident, for they imply that the process equipment (a 10,000 h-p. boiler or a candy kettle) must be suitable for the use of temperature instruments; and that the instrument must be reliable. Most designers and makers of plant equipment now strive to supply industry with apparatus that lends itself to temperature control. And many designers and makers of industrial temperature instruments are capable of supplying control systems that hold temperatures "on the nose" in the majority or classes of processing apparatus—even in some poorly-designed pieces of equipment. The makers of thermometers, pyrometers and automatic systems seem to be several laps ahead. Industrial temperature instruments today are usually more intrinsically accurate than is required by industrial service conditions determined by the "quality" of processing equipments.

It has been a race in which everyone is a winner. It still is. And the friendly rivalry will not only continue but grow in intensity—because all competing groups really compete for the honor of doing most for "the fellow on the other side of the fence"—because Temperature is such an elusive condition to measure and to control automatically that a healthy thirst for exact information unites all workers—because Temperature affects not only all industrial *processes* themselves but all the methods of measuring and controlling the *other* factors that bear upon the success or failure of any technological operation.

"Speeding Up Defense Through Instrumentation"

A reminder that you should enter this $500 prize contest. Details and rules in last month's issue.

Unshakable Foundations of Temperature Measurement

By M. F. BEHAR

BEFORE dealing with temperature instruments, it is well to take up that peculiar thing, Temperature, which they measure and control. This will require that we leave the plant and make a brief visit to the lab and to the lecture-room—but with the understanding that the purpose of this excursion is practical. Let's visit scientists of the past, to whom we owe our bread-and-butter because their discoveries made today's industries possible. Let's visit living scientists whose recent discoveries will put our successors on tomorrow's payrolls.

Come along as you would to a double-feature show—mystery and comedy—for our excursion will combine some of the greatest detective stories with the greatest piece of humor—Nature's impish jokes and riddles.

And it is a huge joke that Nature constantly plays on us. She has given us nine senses which provide the clues wherewith to solve one mystery after another, but to discover her laws we sometimes have to ignore the evidence of these senses. To answer her riddles we sometimes have to fly against the dictates of the trickiest "sense," the tenth one, known as common sense or "everybody knows . . ."

This makes the game exciting, because it takes uncommon sense to solve the ever-springing riddles, and courage to speak out against old petrified common sense entrenched as scientific dogma. It used to be a tough game when whoever succeeded in lifting the veil part way risked being put to death. Nowadays the rules have been softened: instead of the ax or stake, only a "geniuses-are-crazy" handicap confronts modern players. But the accumulation of petrified common sense is greater than ever, and our nine senses weaker than ever, so that Nature's pranks are just as humorous, and the game just as exciting.

For example, Nature has wisely provided every normal human with the sense of temperature, and her joke is that mankind's notions of heat and of "degree of heat" were so ludicrously bound up with this gift that even today it takes several years of night school to pound into a young apprentice the faintest glimmer of modern concepts of heat and temperature in order that he can earn promotions in the plant instrument department. To be sure, science doesn't know all the answers, but classic and modern detective jobs have yielded enough exhibits for a dozen excursions.

The sense of sight is another wondrous gift. Without it we'd be like plants or primordial forms of animal life. Moreover, when Nature endowed us humans with this gift, she acted like a wise and kindly but prankish Communications Commission: assigning to the human eye—and to the human eye only—a reception band of perfect range, perfect shape and perfect location among all her broadest frequencies. If this normal-eye sensitivity curve were much shorter, we'd not only lack the joys of color, but we'd find it harder to distinguish objects. (Ever try walking in a strange place wearing old-fashion pyrometer glasses?) If it were much longer we'd never have the blessed relief of complete darkness when we want to sleep in a warm room (walls and furniture emitting infra-red). But her little joke was that this sense of sight actually prevents us from seeing the whole picture in the entire light, so that it took centuries for scientific sleuths to deduce that radiation frequencies extend over the enormous range whose exploration and utilization leads to progress in temperature instrumentation as well as radio and television.

Our sense of time is a wondrous gift, enabling some of us to wake up regularly a minute before the alarm-clock goes off, but Nature spiced this gift with our "natural" dread of infinite future and infinite past, which made it hard to solve the riddle of Real Geometry. . . .

In connection with the static sense—the sense of balance—there is a long and fascinating history of detection and courage. Nature's gift made mankind able to distinguish between up and down, even in the dark; her joke is that this sense made mankind believe—for a ridiculously long time after we could till, cook, weave, build, read, write and count—in the Absolute Up and Absolute Down. This concept was the official truth; so the earth was flat; the sun, moon, stars and planets were carried by a set of crystal spheres with a common center eternally fixed at Thebes (or Athens or Rome or wherever the Minister of Propaganda declared it was eternally fixed) and off with the heads of instrument-makers and instrument-users who claimed that measurements belied the authoritative texts!

Together with the sense of sight, this static sense constituted a valuable gift in that the combination engendered the concepts of front and back, right and left, of distances and intervals; hence of areas and volumes. But in this case Nature's joke has been (and still is for 99.999% of us) that our space concept made us cowards: we shrank from thinking about "infinite" space and when we couldn't shake off this awe we ran weeping to the medicine-men who had the common-sense answer: "The realm of Jupiter is up above, that of Pluto down below and that of Oceanus all around the earth. Now stop crying; stop thinking; gimme a coupla drachmas for the upkeep of the temple; and if you doubt my word I'll offer you as a sacrifice to the Goddess of Wisdom!" More recently we ran to the genuine astronomers and physicists but—until this century—Nature didn't let anyone see the simple answer with his mind's eye. And that's the answer: the space of physical reality can only be seen by reason's eyes.

As you know, future historians will smile at the pains which nineteenth-century scientific detectives needlessly gave themselves in developing elaborate equations on a quicksand foundation lacking the essential cement of the space-time concept. What has relativity to do with temperature measurement? Why, the simplest visible thermometric effect, the expansion and contraction of a rod (even of a rod of a pure monatomic monovalent metal with face-centered cubic lattice, which is the simplest*) defied all attempts at satisfactory quantitative formulation until about 1935 to 1939. Then only did a few able mathematical physicists put together the main pieces of the puzzle. They did so by making use of modern relativistic theories pertaining to atoms and sub-atomic particles—theories based in turn on Einstein's theories of energy-matter and of space-time field.

Excursion getting difficult?

Stick along: the remainder is apple pie. The idea of this little side-trip was to convey an idea of the handicaps faced by the heroes we are to visit.

* * *

It may have been this natural difficulty which retarded attempts to measure temperature until late in the sixteenth century, when science and technology were pretty well advanced in many other respects. As a matter of fact, the first thermometers (thermoscopes, really) were made in connection with investigations of climate and weather. Galileo Galilei and his associates of the Florentine Academy had been making and using various types of weather instruments, including barometers. The Florence glass blowers were skilled; Galileo himself built hundreds of instru-

**Physically*, of course, the diamond is frequently called the simplest solid because its packing is so close—but *mathematically* this coincidence of tetravalence and four nearest neighbors makes the rigorous derivation of temperature coefficient laws more difficult.

ments of various types and was strong for exact measurements; the concept of temperature was related to human comfort; so it was inevitable, perhaps, that this combination of interests and skills should suggest the making of an instrument shaped like an inverted bottle with a long neck immersed in water, for measuring atmospheric temperatures. The bulb was blown until it was thin, for these workers knew that heat travels slowly through glass. The next step was to use colored water and other colored liquids for indicating the variations in air volume. Next, to make similar air thermoscopes with smaller bulbs to measure the temperature of the human skin. Next, to make various forms with the air bulb at the bottom.

All of these instruments, it appears, were open to the atmosphere, hence uncompensated for barometric error. Cajori relates, in his accounts of the Florentine Academy, that their "scale of heat intensity" was based on two "fixed points, the cold of winter and the heat of summer, dividing the intervening space into 80 or 40 equal spaces. To determine more accurately the position of these points, they defined the one to be the temperature of snow or ice in the severest frost, and the other to be the temperature in the bodies of cows and deer."

"Fixed points my eye!" says someone. But hats off to the Florentines for conceiving the idea.

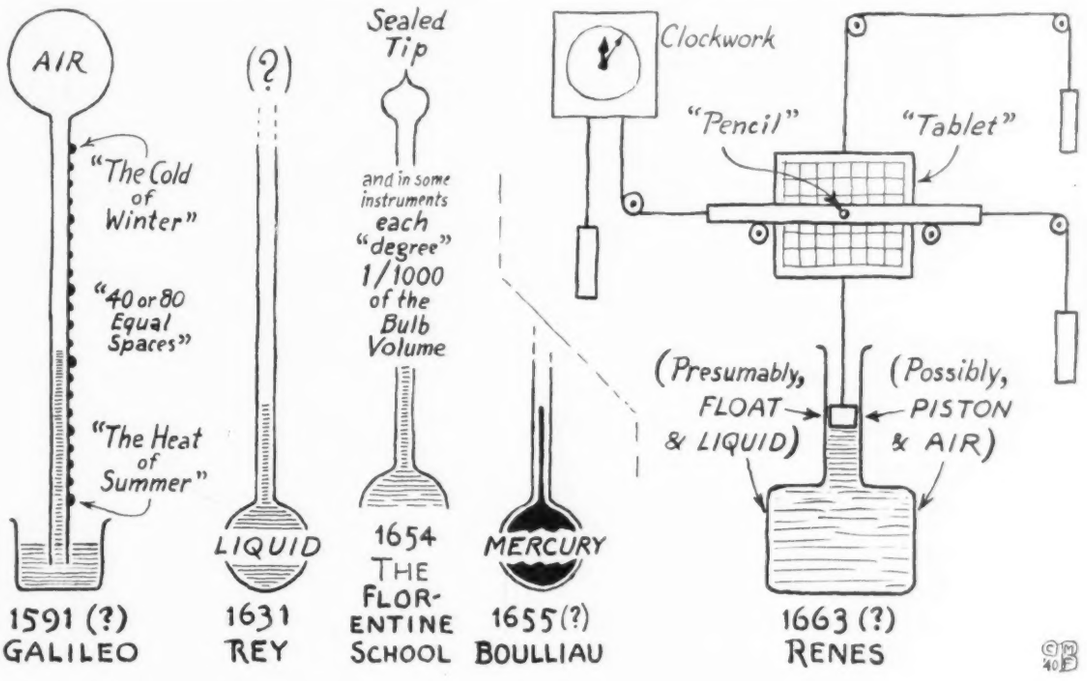
In those days—more than a century before the first practical steam engine—the desire to measure temperature was chiefly entertained by men with a professional interest in weather, medicine and chemistry. A great contribution to thermometry was made in 1631 by Jean Rey, a French chemist and physician. Chemists remember Rey as the first to guess that something in the air was responsible for the increase in weight in what we know as oxidation. Physicians honor him as the first to detect fever by taking the patient's temperature. To instrumenticians, he was the first to use liquids instead of air for the thermometric substance. He used wine, spirits of wine and even water.

In short, he was the founder of liquid-in-glass thermometry. No doubt he tried mercury and discarded it because its expansivity is one-sixth that of alcohol. The outstanding stability of mercury as a thermometric liquid was probably unknown in the 1630's. First to use mercury was the French astronomer Boulliau, whose record of temperature observations from May 1658 to September 1660 is a datum of meteorology.

The year 1665 may be said to mark the dim beginning of the transition from thermoscopy to thermometry: the Dutch-born French astronomer, physicist and instrument-maker Christiaan Huygens recommended using what we would call a *reproducible fixed point*. He mentioned ice and he mentioned boiling water; but it is difficult to ascertain whether he had the right idea of a definite scale interval.

The art made great progress during the remainder of the seventeenth century. Some instruments made by the Florentines compel admiration as masterpieces of glass and enamel work; and they are treasured in art museums as well as in scientific museums. The total number of temperature instruments preserved in art and science museums is said to run into the hundreds.

Only a month before this writing, there was dug up by Dr. Earl H. Brown, a New York consultant in instrumentation, a description of an intricate weather recorder which was in existence in 1663: Monsieur de Monconys, in a book



of travels published in 1695, mentions a visit he made at Oxford on June 11, 1663, to "M. Renes, great Mathematician though small of body, who wishes not that his ideas be divulged but nevertheless told me about his Horologe of the Weather . . ." Then de Monconys describes what we would call a combination rain recorder, snow recorder, wind recorder, recording barometer and recording thermometer. Dr. Brown sent me a copy of the quaint old illustration; and I have extracted and re-drawn the recording thermometer portion of the apparatus.

* * *

Two important milestones mark the beginning of the eighteenth century. In 1701, Sir Isaac Newton developed the first "inferential" method of measuring temperatures: He observed the different times it took to cool an iron bar after heating it to different heats. An inferential method of measurement is one which, though neither positive nor direct, is based on a law of nature. Newton discovered his law of cooling because he had invented a new mathematical tool which he called fluxions and which we know as the calculus. In that same year 1701, Newton proposed a thermometer scale with zero for the freezing point of water, 12 for body heat, and twelve equal divisions. Previously he had calculated what the velocity of sound in air should be at various temperatures! (This in the day of "Nature abhors a vacuum," "anima" and so on!)

A tremendously important deduction was made in 1702 by Jacques Amontons (the man who invented the "telegraph"—a system of signaling spelled-out messages from hill to hill). Amontons said that the absolute zero of the

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intensity of heat must be the point where the spring of the air in an air thermometer vanishes completely.

This was indeed a triumph of observation and reason. Nature gave us the temperature sense as a precious gift, enabling us to survive by avoiding exposures to "very hot" and "very cold" climates or objects that cause death or local injury; but the convenient "range" and "sensitivity curve" of this precious gift has made us unable to know "hotter than hot" or "colder than cold" by actual perceptory knowledge. Amontons was about two and a half centuries ahead of his time. He could not prove his theory. It was not until 1848 that the temperature scale which locates Nature's absolute zero was established.

At this stage of our excursion we may note that Nature has made this particular enigma eternally impossible to solve by a yardstick. No matter what size of a yard we adopt, this yard ("degree") can only measure one interval —the one and only interval between its own two end-points —and it is useless everywhere else. Someone in the party remarks, "Exponential function." He means a yardstick that lengthens and shrinks according to the region where it's used and according to an exact mathematical law. That idea was one of the clues followed by Kelvin (as we shall see) but although it permits us to measure and compare quantities of *heat*, and even to lay out temperature scales that agree with one another and with Nature's, it doesn't give us a yard—not even a rubber yard. For we can add and subtract rigid yards; and we can add and subtract elastic yards by allowing for changes predicted by the law involved; but we can't add or subtract temperatures. We can use a yardstick to measure a mile because a yard "here" is the same as a yard "there" but the physical universe is such that a temperature interval "here" is different from the same temperature interval "higher" or "lower." This is true even if we use a flexible degree of temperature: all the phenomena are different in one region of intensity of heat from what they are in a higher or lower region of intensity of heat.

In fine, temperature is an intensive magnitude.

Furthermore, there is no intensive magnitude like it. Illumination is an intensive magnitude, but how much simpler than temperature! Here is a sheet of paper; above it a lamp with three bulbs; each bulb a source of light and heat. Turn on one bulb, then two, then three: the respective illumination *of* the paper will immediately be in the proportions of 1-2-3 and the respective illuminations *by* the paper will be 1-2-3. But the temperature results will not produce addable figures even if you generalize and idealize the case and count the photons by using a super Geiger counter and applying Worthing's equations.

The glory of the eighteenth-century scientists is that they realized this handicap imposed by Nature in her little game, but nevertheless licked the problem of making some temperature-measuring instruments that could be made to agree with one another. Most cleverly, they took in Nature herself as their partner, by fixing the fixed points of their thermometers in conformity with the fixed points of nature. Two names dominate eighteenth-century thermometry: Daniel Fahrenheit and Anders Celsius, each of whom not only "lobbied" throughout scientific Europe for his system of graduation but preached also the importance of infinite care in calibrating thermometers.* Under the same barometric pressure, Fahrenheit discovered, the temperature of the ice point is always the same. This does not mean merely "ice cold," for a piece of ice may be colder than the ice point, nor does it mean the temperature of a pail of water with cracked ice all around it, for it is possible to cool water slightly below the ice point. The correct description of the ice point is "temperature of equilibrium between ice and water . . ." plus other technical requirements. Fahrenheit and Celsius also made long investigations of thermometric substances and their advantages and defects.

*The name of René Antoine Ferchault de Réaumur is added by some scholars. He was a great scientist; but the naming of a system of graduation after him does not signify that he did as much for thermometry. He proposed a degree equal to 1/1000 of the ice-point volume of a specified kind of alcohol. *By coincidence* the steam point came at 80; but an "0-80" *mercurial* thermometer, called a Réaumur thermometer, does not obey the Réaumur scale law.

What is a thermometric substance? No exact definition is possible. Every material body is thermometric in the sense that heat and cold change it in one way or another. Some substances exhibit effects which are more reliable than others. The best substances, in fact, are those which behave so well that we can forget them and concentrate on the *effect* which we utilize. (While on duty at the board, we feel better when we can concentrate on the record produced on a recorder chart than when we have to think of the mechanism of the recorder.)

The eighteenth-century investigators discovered that spirit thermometers carefully marked at the ice point and steam point would agree with one another when they were filled with spirits of specified manufacture and purity. So would well-made mercury thermometers. This led to another discovery, namely, that the scales of "perfectly accurate" thermometers employing different substances did not agree in the region half-way between the calibration points, and that the discrepancies were even greater between well-calibrated thermometers employing different observable and measurable *effects* of temperature.

Most bodies expand with rising temperature; some show little change; a few actually contract when heated and expand again when they cool. (Some alloys of the invar type, produced by clever modern metallurgists, have what is known as a negative coefficient.) Some substances display *bad* manners (the technical word is *anomalous*). Water, for example, is so ill-behaved that when you heat it from the ice point to the steam point it starts to shrink coyly, then changes its mind at 4° centigrade and expands from then on. (But if that were not so, there would be no human life on this planet.)

The eighteenth century had begun with the first bit of quantitative pyrometry—Newton's inferential measurements of high temperatures which before his day could only be described as "cherry hot," "white hot," etc. Its end witnessed another advance in pyrometry, which began in 1782 when Sir Josiah Wedgwood, maker of artistic porcelain, announced his famous shrinking clay cylinders. The title of mometer for measuring the higher degrees of Heat, from his Royal Society paper was "An attempt to make a Thera red heat up to the strongest that vessels of clay can support." He established a scale of temperature based on shrinkage of standardized clays, made to exact dimensions. Prompted by an Edinburgh professor named William Playfair, he then attempted to make this scale conform to the Fahrenheit scale of mercury expansion, and he obtained a number of high-temperature measurements. Let us examine three of these:

Melting Point of	*"Wedgwood-Fahrenheit" Scale**	*Modern Fahrenheit Scale*
Silver	4,717	1761
Cast iron	17,977	2175†
Wrought iron	21,637	2750

*As reported by A. Dodds, *The Instrument World*, Vol. 4, Oct. 1931, page 108.
†White cast iron 2100; gray cast iron 2250.

Don't laugh! Wedgwood was the victim of one of Nature's little jokes: He assumed that the graduations obtained by such a reliable effect as the contraction of his standard clay cylinders represented a scale of intensity of heat which, if uniformly calibrated in its lower region, could be continued uniformly all the way up to the intensities of heat in his world-famous kilns.

Why shouldn't he assume that? At the beginning of that century Amontons had imagined a scale based on the "spring of the air" and had dared to extend it mathematically all the way *down;* and for the past eighty years an ever-increasing number of men of science had been saying that Amontons was probably right. Only recently, in 1779, Lambert in his widely-read *Pyrometrie* had mathematically deduced a value for "absolute cold" which was 2.70 times the interval between the ice point and steam point. Why shouldn't Wedgwood extend the mercury scale *practically*, only a little way *up?* There's no reason why he *should* not. He just *did* not! He did not really extend Fahrenheit's

mercury-expansion scale above the boiling point of mercury. And Amontons had not really extended the air-volume thermometer scale below the freezing-point of his colored-alcohol indicator.

Amontons and Lambert, by the way, were not the only ones to try to "extend the scales" of actual thermometers on the cold side by imagination. Others had speculated likewise. Their inferential measurements of the "number of degrees" down to absolute cold disagreed enormously. The results of Laplace and Lavoisier ranged from fifteen to thirty times the ice-to-steam interval. Dalton adopted 30 times that interval. Refrigeration engineers had not made their bow, so there was no actual production of colds below mixtures of ice and salts and the measurements of such colds remained a matter of speculation. But "the higher degrees of Heat . . . up to the strongest that vessels of clay can support" were being produced every day in various industries and their measurement was a practical need. Wedgwood was a measurement-minded manufacturer. He "put in an instrument department" in his plant and ran it himself. In developing "high-temperature instrumentation," he used the "overlapping ranges" technique as well as he knew how. And no Instrument Department can do better than that!

What was wrong?

Nothing. Nothing much, that is, except that the clay cylinder contraction scale did not agree with others, such as the metal bar expansion scale, in the regions of multiple overlap. "Then which of the scales of these competitive instruments," we can imagine ceramists asking, "is the legitimate one for measuring red heats?"

"All are legitimate; none is inherently a Standard," we can imagine Science replying.

"Oh, but that's intolerable! Isn't there a way we can select one in preference to all others—say like a mariner's chronometer is preferable to an hourglass?"

"You've got something there," says Science. "The logical choice should be Newton's method of plotting the easy-to-get-at endings of cooling curves and calculating the degree of heat of the furnace from which the bars were withdrawn. His method is correct, as far as we know. But it is not an instrument. It is an extremely complicated and difficult technique, in which new sources of error are being discovered with every attempted refinement."

"Well, what's the answer?"

* * *

The answer was hard to wrest from Nature, but it was bound to come as a result of two events that happened in 1769. One event was the granting of the famous Heat Engine patent to James Watt; the other was the birth of a son to a Corsican family named Buonaparte. By the beginning of the nineteenth century the two consequences—the industrial revolution and the clash of world empires — both yanked men of science from their seclusion and spurred them to solve hundreds of riddles to improve the efficiency of manufactures and the effectiveness of armaments. Shortly after the Napoleonic wars, it was to be expected that the son of a former Minister of War, a brilliant graduate of the École Polytechnique, should devote his talents to improving French armaments in order to vanquish "those manufacture-minded Britishers who would rather listen to a steam engine than to a symphony." But this young Lieutenant of Engineers, named Nicolas Léonhard Sadi Carnot, sought by measurements and calculations the answer to the question, "How efficient can a heat engine be?"—and he found this answer by a triumph of inductive reasoning involving also the first tentative answer to the question, "Just how can we measure temperature and know we're doing it right?"

Carnot's memoirs are the foundation of thermodynamics —an essentially mathematical science which we must avoid here. Let us go back to the end of the eighteenth century and attack the problem of making thermometers that agree with one another; and in that way we shall see how it came about that the invention of the steam engine, and the demands by "sordid tradesmen" that it be made more and more efficient, gave the greatest impetus of all time to temperature measurement.

Let us take a number of substances—some which Fahrenheit, Celsius, Wedgwood and other thermometer makers recommend as good substances to work with, and some substances which they have not tried. Next we take an inventory of the precision instruments at our disposal: balances, manometers, chronometers, etc., so that we can accurately measure the effects of temperature on these solids, liquids and gases. Then we proceed to make exact measurements of these substances at the ice point, and other exact measurements with these substances at the steam point.

It doesn't matter what yardsticks we use except that the same yardstick must be used for the ice-point measurement and for the steam-point measurement of the same effect of the same substance. For example, one experiment gives us a reading of 24.7 at the ice-point and a reading of 26.0 at the steam-point, every time it is performed. This substance and its effect, then, may constitute a thermometer. On the blackboard we draw two vertical lines separated by a convenient distance—representing the temperature interval between the ice-point and the steam-point. We graduate each line in convenient units. On these two lines we mark the points *a a* and through them we draw the line *A*. We extend this line on both sides—on the colder side at the left and on the hotter side at the right. This is a scale of temperature, as legitimate as any to the best of the knowledge we gained from experiment *A*.

We then have a flock of careful observers make a flock of experiments in the same manner on a flock of other substances; and we get something like the blackboard diagram but with a far greater number of connecting lines and extended lines, because we are making a whole flock of experiments—not merely nine as plotted on the blackboard.

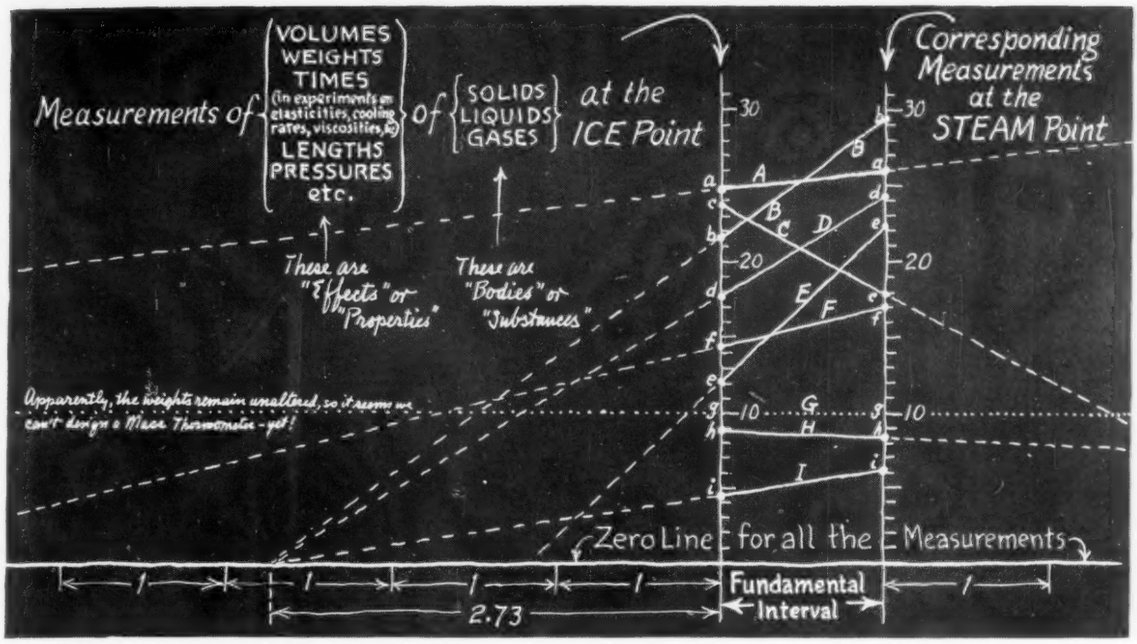
Our observers, by the way, have reduced to one line on the blackboard each series of experiments giving concordant results for a number of substances. Most important is line *G* for it applies to *all* substances. Yes, all substances, they report, weigh the same at the ice-point and at the steam-point. That's a negative discovery, so to speak, but a conclusive one, proving that caloric (our eighteenth-century name for heat) neither gravitates nor levitates. We have proved that caloric is an *imponderable* as well as invisible fluid. We would laugh scornfully if someone said that maybe in the twentieth century a scientist might theorize, among other things, that a body weighs a wee bit more when it's hot than when it's cold, and that the proof of his theory would have something to do with the orbit of Mercury with a capital M.

Even as simplified, the situation looks rather confused, except for the clue that gas volume and pressure experiments seem to hit the same spot on the base line—a point about 2.7 times the "distance" between the ice-point experiments and the steam-point experiments with gases. So report Lambert and other observers now at work (in the 1780's). Amontons must have been a pretty good guesser 'way back in 1702!

We can't be too sure, though, because the points *e e*, though identified only by the one letter *E*, represent a great number of experiments pertaining to cooling rates, viscosities and other measurable effects; and when observers had made extra measurements with thermometers *B*, *D* and *F* at a temperature about half way between ice and steam, they had said that this line *E*, **in comparison with the others**, should not be straight: it should shoot up more and more rapidly as the temperature increases.

Which is the preferable substance?

Carnot answered "There is no such thing!" He defined, however, the ideal working substance of the perfect heat engine, by defining a "reversible thermodynamic engine." It is no news to you that the only perfect "things" in Nature are those which are the concepts of bold yet precise imaginations. They are the mathematical realities which not only make exact measurements possible, but make predictions possible. For example, the jelly-like "ether" of Maxwell not only carried electricity when Edison, Steinmetz and Westinghouse were young experimenters, but it predicted the waves of wireless telegraphy and radio. Carnot's achievement shines even brighter when we remember that he worked under a handicap: according to prominent scien-



tists of his day, heat was not energy but the invisible imponderable fluid named caloric. That handicap was not finally removed from Nature's guessing game until after Carnot's death.

Carnot's efficient heat engine is important to us because its efficiency depends on the temperatures between which it works. He used it to prove his famous Principle, that the mechanical power obtainable from heat is independent of the agencies employed to realize it: this efficiency depends exactly on the temperature of bodies (cylinder walls, condenser tubes, etc., and the "working substance") between which there is a transfer of heat. As Clausius later put it: "The performance of work is equivalent to a transfer of heat from a hot to a cold body without the quantity of heat being thereby diminished." There you have it! If there is both mechanical and thermal equilibrium between the working substance and actual material surfaces at every stage of the cycle, the heat engine will be perfectly reversible. Thermal equilibrium? That means *no* temperature difference! To make a long story short, Carnot's mathematical description contained a "function" (never mind what that is) which remained constant, and was the same for all substances at the same temperature, thereby tending to show that the caloric theory was all cock-eyed. Carnot himself was so modest that he merely wrote "Many experimental facts appear inexplicable in the present state of the theory . . ." Well, there was a hullabaloo, and even today Carnot's Function finds a prominent place in books on heat engineering. Today we know that heat is energy and that this function serves to define what temperature is—although this exact definition of temperature was not formulated until thirty years after 1824!

* * *

Another coincidence: Carnot published *The Motive Power of Fire* in 1824. That same year William Thomson was born in Scotland. At the age of 24, young Bill Thomson took hold of Carnot's ideal substance and gave us the scale which all the world's temperature instruments are calibrated against, through the National Bureau of Standards and the similar national institutions, and down to us by way of the instrument companies' laboratories. You know why it is known as the Kelvin Scale: Bill soon became Sir William Thomson and then Lord Kelvin.

Like many sublime achievements of genius, Kelvin's rigorous definition of what temperature is can be understood by any boy in Junior High—even by a bright boy in the grades. What he did, in effect, was to take the schoolboy definition, "Temperature is the degree of sensible heat of a body," and put it into Carnot's thermodynamic terms. Kelvin defined the ideal thermodynamic scale of temperature as such "that the absolute values of two temperatures are to one another in the proportion of the heat taken in (Q_2) to the heat rejected (Q_1) in a reversible thermodynamic engine working with a source and refrigerator at the higher (T_1) and lower (T_2) of the temperatures, respectively."

Do you recognize the schoolboy definition in Kelvin's use of Carnot's terminology? It is there. For "sensible heat" in the schoolboy definition (which implies properties of substances) Kelvin substituted the *available energy* that can do work in power plants, in the chemical industries, in the blast furnace and in the kitchen refrigerator. While he did not use these words, they are obvious to modern readers, and we sometimes speak of Kelvin's "energy definition" of temperature.

But that energy definition was only half of what was done by the young physicist. He took the vague first part of the schoolboy definition, "the degree of," and proposed instead a *scale of availability* of heat energy in an ideal "body," thereby giving us the first scientific standard for the measurement of temperature—The Absolute Scale of Temperature.

Speaking of science, we must be exact. Kelvin's definition was in a way too independent of properties of matter. His scale could only be seen with the eyes of reason. It was not until 1854 that he defined the absolute temperature (the capital T or K of calculations) as proportional to the reciprocal of Carnot's function, and that he began with Joule the porous plug experiments which allowed him to announce in 1862 the practical application of the absolute scale in the making of tangible thermometers with visible scales.

These two men—and many other workers—had begun what is known as the *realization* of scales which are independent of properties of matter. There being no "ideal body," an ideal gas thermometer could not be built, but the absolute gas scale was defined and *its* realization begun. The deviations of actual gases from the laws could be and were determined, and actual gas thermometers could be and were built, and their readings corrected to give values that were unquestionable.

It is plain to see the importance of "ideal" scales independent of properties of matter and based on The Absolute Scale of Temperature. We use thermometers when we want to know "what the temperature is." These thermometers are calibrated by reference to fixed points. There *is* a zero, of course, the absolute zero, but it is as impossible of attainment as perpetual motion.* We must use "easy" fixed points.

*This flat statement is allowed to stand word for word as in the first edition (1930) although we take back our old footnote elaboration concluding with the statement that "To deprive a body entirely of heat is impossible." It seems that such a fine distinction is imposed by newer implicit definitions of heat and temperature.

But to measure these fixed points we must use thermometers. But we cannot construct a perfect thermometer. But we need properly scaled thermometers to measure unknown temperatures. Round and round it goes—or it would go round and round without a solution unless we had a standard of measurement for comparison.

Together with the gas laws, Kelvin's thermodynamic scale provided one such standard, as we have seen. And the gas thermometer, made to definite specifications, was the tangible representation of it.

Gas thermometers could not be used successfully at temperatures injurious to their physical parts, and therefore other laws and effects had to be selected to produce new scales corresponding to the thermodynamic scale and therefore to the absolute scale of temperature.

At this stage of our excursion we leave our hero, Kelvin, and meet Josef Stefan and Ludwig Boltzmann whose achievement, said to be as magnificent as Kelvin's, is nevertheless more easily understood.

To measure temperature with a thermometer in the usual way, the sensitive part of the instrument must have come to thermal equilibrium with the "body"—or in reality with the *material substance*. There must be contact, and heat must flow one way or the other by conduction or convection until equilibrium is established. To break the shackles with which imperfect actual substances fetter us, Kelvin defined the ideal thermodynamic scale in terms of Carnot's thermodynamic body. This was (or we may venture to call it) a *conduction-convection* ideal body. But equilibrium may also be brought about by *radiation*. Must there be contact in order to perform an accurate measurement?

History repeated itself: The first piece of detective work was done in 1858 when Balfour Stewart proposed, and in 1859 when Gustav Robert Kirchhoff defined, the *radiation* ideal body—the "black body"—by proving that radiation as a function of temperature is independent of its source. And up rose the cry, Can we use the Kirchhoff black body in some temperature "effect"? Has it a temperature property"?

Yes, said Stefan in 1879, the radiation *between two black bodies* varies as the difference of the fourth powers of their absolute temperatures. The radiation between a black body at a temperature T and a black "radiometer" at a temperature T_0 is proportional to $(T^4-T_0{}^4)$. No conduction here, as there was in Carnot's cycle with its two reservoirs. Fair enough. But where is the *proof*? How about *measuring* high temperatures? Can we define a new scale without abandoning the Carnot-Kelvin capital T?

Yes, said Boltzmann in 1884. Correspondence of scales can be proved by substituting radiation for the "working substance" in the Carnot cycle. Radiation energy at any temperature, within or above the accepted gas scale, per unit volume, is proportional to T^4.

Stefan discovered the law; Boltzmann proved it. It therefore is known as the Stefan-Boltzmann Law and is the foundation of radiation pyrometry. The electrical-instrument scales of radiation pyrometers can be calibrated in degrees up to temperatures that vaporize the most expensive refractories.

How is it that the electrical-instrument scales of radiation pyrometers can be made to correspond? Let's take a little side trip—a brief one over familiar ground. Again we start with the 18th century — just about the time that Wedgwood was putting in his "plant instrument department." It was in 1780 that a student of frog's nerves and muscles noticed a strange phenomenon—the first of many galvanic phenomena, thus named because the student was Luigi Galvani. We can skip to the twenties of the 19th century (the time of Carnot's studies) when a number of scientists were experimenting with galvanic and voltaic apparatus—coils and wires of various metals, magnetized needles, coils made into magnets, etc. It was inevitable that the effect of temperature on the resistance of a thin wire should be detected, around the 1820's and also the flow of current in a circuit consisting of two different metals with their junctions at different temperatures. Resistance thermometers with calibrated instruments did not appear until electrical instruments became practical devices, between 1870 and 1890. Likewise, although Seebeck discovered the thermoelectric effect in 1822 and Becquerel in 1826 made the first thermocouples for measuring temperatures, the development of practical thermoelectric pyrometers had to await the manufacture of electrical instruments.

Electrical methods, employing resistance effects and thermoelectric effects, soon grew in practical importance to industries for two reasons: First, of course, the refinement of instruments, the standardization of materials, and so on. Second—more important from the point of view of this excursion—their scales could be calibrated by reference to the Carnot-Kelvin ideal scale. Therefore, because radiation pyrometers embodied resistance coils and thermocouples *their* scales could be made to conform to the Stefan-Boltzmann radiation scale . . . Now back to the main route of our excursion.

* * *

Up to now, the "radiation" we were considering was, of course, the *total* radiation between two Kirchhoff black bodies.

But, from ancient times, common experience had disclosed an altogether different effect of great intensities of heat—a visible effect. From ancient times blacksmiths and swordmakers had observed that the hotter a piece of metal, the brighter it glowed. "Red hot" and "white hot" also conveyed fairly definite ideas whereby masters taught their apprentices. More modern measurements by various methods half a century ago resulted in useful color charts up to what the printed instructions called "intense white." Could not a "brightness" scale be proposed, it was asked in the nineties, so that brightness pyrometers could be constructed with scales agreeing with the new radiation scale and hence with the extended standard gas scale? Furthermore, while the Stefan-Boltzmann Law expresses the relation between temperature and radiation without reference to color or wave-length of the radiation, could not "change of color" with temperature, or the relation between wave-length and temperature, be also expressed as a law?

Not one question, this time, but two.

We can start from an easily remembered date. It was in 1800 that Sir William Herschel used a prism and a sensitive thermometer, and discovered that the thermometer not only read higher at the red end of the spectrum of sunlight, but that it read highest far away from the red edge of the beautiful spectrum, well into the region where his sheet of white paper was in total darkness.

Then, just about a hundred years ago, Nicéphore Niepce and Louis Daguerre started what has led to that hobby of minicams and amateur movies. The early photographers soon discovered that the red end of the spectrum did little to the emulsion, the blue region did most of the work; the violet end which is so difficult to perceive by eye worked strongly on the photographic plate; and the invisible ultraviolet rays, for a short distance at least, likewise performed the same trick with the silver salts in the emulsion. Thus a baby named spectroscopy was born to papa prism and mamma photography—or the other way around if you want. That blessed event occurred around the middle of the 19th century.

Telescopes made available those inimitable high-temperature sources, the blue stars.

And now began a long series of investigations, by detectives too numerous for any single excursion-conductor to remember, which disclosed a number of amazing facts.

The radiation from any material body is not evenly distributed among the various wave-lengths but it is always shaped like a hill. At the ends of the two slopes of this hill, the rays are extremely feeble, dwindling down to zero elevation almost imperceptibly.

The radiation emitted by a black body is a continuous spectrum. The hill is not interrupted by vertical cuts as it is sent out. However, a material medium cuts off some of the wave-lengths, sometimes sharply and sometimes gradually. Thus, a piece of red glass is one that has a hill of its own. The peak of this hill is called the effective wave-length.

Likewise, a material substance which is not a black body broadcasts over a set of frequencies which vary in pattern, in distribution and in relative intensities.

(Continued on page 268)

Classifications of Temperature Instruments Can Serve as Practical Tools

By M. F. BEHAR

This subject may be introduced by quoting C. O. Fairchild, co-author of the famous book *Pyrometric Practice* issued by the National Bureau of Standards in 1920: He likes to point a moral by mentioning that before electric time was installed at the Bureau, any clock appreciably affected by temperature changes provoked the remark: "That clock is a good thermometer!"

In point of fact, a temperature-sensitive timepiece is one kind of classifiable temperature instrument. The thermometric property involved is the temperature coefficient of rate.

E. D. Frost, former Director of Yerkes Observatory, wrote in 1931 that by counting the number of times a cricket chirps per minute and applying a simple formula, one obtains the air temperature in degrees Fahrenheit. Thus, the normal specimen of a saltatorial gryllid orthopterous insect (or perhaps only *Gryllus domesticus Illinoisicus)* is a kind of temperature instrument. So are the other chirping insects. So are all insects. (So are swarms of insects; the number of bees flying out of a hive per minute bears a pretty accurate relation to temperature.) So are all cold-blooded species; their blood temperature being that of their surroundings, their heart-beat rate and other organic rates are all functions of ambient temperature. The thermometric property in all these biological cases is always the temperature coefficient of rate—just as in the first example!

Crystal oscillators monitoring radio transmitter frequencies are kept in carefully thermostated enclosures because of their high temperature coefficient of natural rate. To call these crystals "good thermometers" would not be funny: it would be the simple truth. Similar crystals *are* used for temperature measurements, the attainable accuracy being commensurate with the extreme precision of modern frequency-metering equipments.

Horologists and others with a practical, occupational or financial interest in time measurements would perhaps insist that a classification of temperature measuring instruments should recognize the above-mentioned thermometric instruments (and "instruments") as *one distinct class*, characterized by the temperature coefficient of rate.

They would be justified. Classifications of measuring devices prepared for reference use by practical men in industry must bring out (or at least suggest) the various ways in which practical problems may be solved. Apprentices studying such lists in evening courses or in their spare time must have their thirst for knowledge satisfied. So must the students regularly enrolled in engineering schools with formal courses. Each occupational group in a plant instrument department must likewise be considered.

It is impracticable to satisfy all groups by preparing a hundred complete lists of instruments, each arranged in such a way as to bring out the information of specific value to one group.

As a compromise, a number of brief classifications are given below, each representing a distinct point of view. There will also be given fairly comprehensive classifications. So great is the number of different varieties of temperature instruments that it becomes necessary to group varieties into types, types into classes, and classes into broad divisions. Any list of broad divisions, however, may be made complete. Thus we have the following examples:

(A)	(B)
1. "Scientific"	1. "Laboratory"
2. "Industrial"	2. "Plant"
3. "Domestic	3. "Field"
4. "Universal"	4. "Universal"

(C)	(D)
1. Contact	1. Local
2. Distance	2. Telemetering

(E)	(F)
1. Indicating	1. Portable
2. Maximum- or minimum-registering	2. Board- or wall-mounted
3. Recording	3. Built-in
4. Controlling	4. Convertible
5. Combination	
(G)	(H)
1. Single-point	1. "Ready-to-use" or "factory calibrated"
2. Selector-switch type	2. Requires calibration

Another way to classify temperature instruments is by quantitatively graded categories, defined by arbitrary intervals like size classifications, weight classifications, etc. Such categories, in their ideal forms, have methematical differentials for their dividing lines. Their logical use is as supplemental references. Examples:

(I)	(J)
1. Limits of practicable ranges extend from 0°Abs. to 100°Abs.	1. $4.99 or less
	2. $5.00 to $99.99
	3. $100 to $499.99
2, 3, 4, etc. Similarly defined	4. $500 to $999.99
	5. $1000 or more

All of the above are simple and obvious, but combining them in various ways is a good classroom exercise in instrumentation courses—as well as a means of making decisions in the plant. Note that only a few combinations are possible. However, the combination of types from two or more different lists should be carried out throughout this chapter. In particular, classification (F) should be placed opposite several which appear below. Busy purchasing engineers will actually find such "exercises" a time-saving tool. All readers should bear in mind that many industrial temperature instruments are usually made up of standardized components, some of which are embodied in instruments for measuring and controlling other conditions than temperature.

Thus, the part of a "gas-filled type recording thermometer" which is installed on a panel board is essentially a "recording pressure gage." A man who services such recording thermometers in a plant has to think of them (at least part of the time) as pressure-measuring devices. This is true of the men who have designed, sold, purchased and installed these recorders. Nearly all panel-board instruments thus "belong" in several classifications. To look at a self-balancing electrical recording instrument, you cannot tell (unless you read the name-plate or the printing on the chart) whether it is connected to a hydrogen-ion concentration cell, to a radiation-receiver tube, to a resistance coil or to a gas-analysis cell. It might be recording the frequency of an alternator in a hydroelectric plant two hundred miles away.

A self-balancing potentiometer or bridge is an intricate electro-mechanical assembly, requiring expert workmanship. It has been designed and built by specialists whose thorough and long experience need not have included the measurement of pH, or of frequency, or of temperature, or of gas mixtures. In industries where such instruments are used, the maintenance men who take care of them have to think of them (at least part of the time) as electro-mechanical assemblies regardless of the types of thermocouples or chemical analysis cells to which they are connected.

However, the maintenance man in an industrial plant—and in general the *user* of temperature instruments—or any student of temperature instrumentation—should think of gas-filled type recording thermometers, and of recording type radiation pyrometers, as both belonging under Temperature but as being distinguished by their respective principles of temperature measurement. Likewise, to the reader of this book the differences between two temperature recorders of the same design, make, etc.—one connected to a radiation receiver and the other connected to a resistance

coil—are more important than their similarity at their respective panel-board ends (where the two recording instruments are much more nearly alike than two peas in a pod). A chart boy who intends to "join the cops" when he grows up thinks they are alike; and the only difference he knows expertly is that "number 16 in Mr. White's department" has a new kind of non-clogging pen; another chart boy, ambitious to succeed "Mr. White," is *studying what's back-of-the-board*, and he already knows why the boss classifies these recorders into distinct categories.

Standardization and interchangeability create interesting possibilities in all technical fields; but in temperature measurement these possibilities are probably the most fascinating as well as the most fruitful of practical results. Thus, if instead of starting from the control-board end of a temperature instrument system, we start from the primary-element end, possibilities are discovered which can help solve various practical problems. The radiation pyrometer furnishes an excellent example. A radiation pyrometer, in its simplest form, is an arrangement for focusing radiant energy upon a wafer-like disk, this disk being blackened in order that it should absorb nearly all radiant energy and reflect little. That is the essential part. From this point on, the classification of the radiation pyrometer will depend on what kind of a device may lurk beneath its blackened disk:

(K)

a differential-expansion device (bimetallic spiral),
an electric-resistance wire,
a mercury-expansion device,
a gas-expansion device,
a thermoelectric device,
a thermionic device,
a blocking-layer device,
a crystal oscillator,
a glass cell containing a liquid that shows a resistance change,
ditto a turbidity change,
ditto a pH change,
ditto a polarization effect,
ditto a crystallization effect,
and so on. (Today's theory is tomorrow's practice!)

Automatic controllers are universally classified, among other ways, into: (1) self-operating; (2) relay types which can be used where a suitable source of auxiliary power is available. Among these sources are

(L)

Compressed air,	Gas,
Water pressure,	A. c.,
Oil pressure,	D. c.,
Mechanical power from nearby shaft	Steam, etc.

and some forms of power are utilized in the operation of relay type recorders as well as relay type controllers. In recent years there has been a great increase in relay type instruments, making necessary a classification of pilot devices. Again starting from the primary element, but with the understanding that this primary element itself performs a measuring function, we give a classification of primary relays—the classes to choose from in considering how a given measuring element may, without "drag," command the operation of the power-driven elements:

(M)

1. *Pneumatic.* Mostly made up of compressed-air devices but includes warm vacuum systems and gas-operated systems. Characteristic feature of the usual dead-end and bleed arrangement is a single controlled-air line between pilot and power device, so that the action is undirectional. (Secondary pneumatic relay systems—"valve positioners," etc., provide micrometric lock-in.) Some are double-action systems comparable to the hydraulic class.

1A. *Steam.* Shares some characteristics of the pneumatic class and of the hydraulic class. Most conventional steam pilot valves operating double-action cylinders, require so much energy for their actuation that only the relatively powerful primary measuring elements can actuate them without suffering impaired sensitivity.

2. *Hydraulic.* Comprises all systems where an incompressible fluid is the operating medium. Oil is most frequently used. Positive operation and possibility of locking-in-place of power cylinders are the most obvious characteristics. Drag effect has been minimized in the newer pilots and almost eliminated in the pivoted "jet pipe" relay.

3. *Mechanical.* Various types of escarements, clutches, triggers, torque amplifiers, etc., operating mercury switches, electric contacts, electric-motor chart drives, etc.

4. *Electrical.* Majority are "on-and-off" devices. Simplest are contacts directly attached to the pointer. Single-contact, high-low, and three-position. Next come true electromagnetic arrangements actuating power relays with relatively high ratings (great variety of switchgear). Some step-by-step, others continuously-variable. The effect of a continuous variation is obtained by vibrators and other circuit-interrupting devices whereby the closed-circuit time in each cycle is a function of the position of the pointer. Inverse-time relays may have periods up to five minutes, down to 1/120 second.

5. *High-frequency Electrical.* This class utilizes the properties of a-c. networks. Outstanding characteristic is the possibility of eliminating drag by doing away with the contacts and pilot valves. Pointer serves as one plate of a variable capacitor, or as the control element in an inductive coupling, etc. Or, relay action is effected *without any mechanical motion at all*: used in conjunction with "static" measuring systems in which the measured temperature is translated into a proportional electrical magnitude, which need not itself be an a-c. effect. (Relay systems of this class are erroneously called "electronic" in most catalogs.)

6. *Electronic.* In this class the relay proper is an electron tube, directly actuated by or fed from the measuring element or system. Principal characteristic is suitability for actuation by static measuring elements. Conversely, no ordinary pointer-and-scale type of measuring element can be equipped with an electronic relay and no ordinary type of electron tube can serve as a relay in conjunction with a mechanical-displacement type of measuring element.

7. *Photoelectric.* This class comprises both phototubes and photocells. The former should not be lumped together with the electronic relays. For our purpose the only criterion is that electronic relays respond to purely electrical effects and have purely electrical outputs; whereas photoelectric relays are all those which respond to light and have electrical outputs.

The point of view of a particular industry attaches importance to specific functions. In the ceramic industry, for example, the fact that pyrometric cones satisfy requirements is more important than the fact that they have no pointers and scales. The specific fact that a cone slumps at its end point, however, suggests two more ways of classifying temperature instruments:

(N)	(O)
1. Continuous scale — the usual form	1. Measures once and is discarded
2. Discontinuous scale consisting of a series of units	2. Measures intermittently (max. & min., etc.)
	3. Measures continuously

Still another classification—the most important fundamental classification of all—is suggested not only by the slumping action of fusion cones but by a consideration of all utilizable effects of all temperature properties of all substances.

The whole practice of temperature measurement is founded on the "fixed points" and the international standard is defined by a scale with a fundamental interval of 100 degrees between the ice point and the steam point. It always is because of a *discontinuous* effect of heating or cooling a substance when it undergoes a change of state that this substance has temperatures of equilibrium. Such effects are always *reversible;* and the combination makes possible the use of these fixed points. Therefore the basic methods are those which utilize *discontinuous reversible* effects. The great majority of methods used in practice, of course, are based on *continuous reversible* effects. A pyrometric cone is an example of a *discontinuous irreversible* effect.

This classification of instruments by the utilized effects being the most important of all, it has been attempted for the first time—and carried out through all of the divisions, most of the classes, some of the types and even a few varieties. See Table I: although it is far from complete in detail, its framework of mutually-exclusive categories is believed to be a collectively-exhaustive list.

Men in charge of the calibrating sections in plant instrument departments are chiefly interested in classifications of methods. For their use (and that of educators, advanced students, instrument engineers, etc.), three possible classifications of fundamental methods of measurement are given:

(P)	(Q)	(R)
1. Direct	1. Positive	1. Null
2. Indirect	2. Inferential	2. Deflection

The traditional classifications are largely based on definitions, some of which have been obsolescent for several years. Table II* follows traditional lines except in distinguishing between visual and automatic "optical" pyrometers. It purposely omits a great number of varieties (and even "types") of no readily-apparent commercialization possibilities, or of slight industrial interest.

Following are a few definitions, "as presented by the Industrial Group of the Association of Scientific Apparatus Makers, after discussion with the Bureau of Standards and other authorities":

1. *Thermometer.* A device for measuring temperatures.
2. *Pyrometer.* A device for measuring high temperatures. The term is applied to those devices, the principal use of which is for measuring temperatures above a red heat (about 500°C. or 932°F.).
3. *Resistance Thermometer.* A thermometer which indicates temperature by means of the change with temperature of electrical resistance of one of its parts. It is a pyrometer when used at high temperatures (above 500°C. or 932°F.), and in such case is preferably called resistance pyrometer.
4. *Radiation Pyrometer.* A pyrometer which indicates temperature by means of the change with temperature of the heat radiated by a hot body. As nearly as possible the total heat radiated is used. Usually this temperature is measured by thermocouple.
5. *Optical Pyrometer.* A pyrometer which indicates temperature by means of the change with temperature of the light emitted by a hot body. As nearly as possible light of a single color (wave length) is ordinarily used.
6. *Thermocouple.* A pair of electrical conductors so joined as to produce thermal e.m.f. when the junctions are at different temperatures. It consists of conductors of different material permanently joined at one end, the other ends being free to connect to an instrument for measuring e.m.f.
7. *Thermoelectric Pyrometer.* A pyrometer which indicates temperature by means of the change with temperature of the e.m.f. of a thermocouple. It ordinarily consists of a thermocouple, a millivoltmeter (or other means of measuring e.m.f.) and connecting leads. The measuring instruments may be classified as follows: millivoltmeters; potentiometers; their combination of modifications.

*Merely a slight revision of Table II in the first (1932) edition of this book.

TABLE I
CLASSIFICATION OF TEMPERATURE INSTRUMENTS BY THE MEASUREMENT METHODS EMPLOYED

I. Methods Utilizing Discontinuous Reversible Effects

1. *Freezing point.*
2. *Boiling point.*
3. *Solubility.*
4. *Surface color.*
   (thermoscopic paints, etc.)

Etc.

A line must be drawn (both meanings) between equilibrium temperature effects which include the International Standards, and all others.

II. Methods Employing Continuous Effects

1. *Properties of bodies.*
   a. Thermal expansion, expansivity, expansibility.
      (1) of gases
      (2) of liquids
      (3) of solids
      } Instruments are classified by utilized coefficient (linear, cubical); also as cathetometric, extensometric, volumetric, etc.
   b. Viscosity, fluidity.
   c. Conductivity, resistivity (electrical).
      (1) of metals, of alloys.
      (2) of other solids.
      (3) of electrolytes.
      (4) of ionized gases, etc.
      Etc.
   d. Refractivity.
   e. Vapor pressure.
   f. Magnetic susceptibility.
   g. Sound velocity.
   h. Dielectric power factor.
   i. Elasticity.
   j. Specific rotation.
   k. Color of transmitted light
   l. Color of reflected light
   Etc., etc., etc.
2. *Effects between bodies.*
   a. Simple differentials of properties.
      (1) Expansivities.
         (a) Bimetallic.
      Etc.
   b. Effects at interfaces.
      (1) Solid vs. solid.
      (2) Solid vs. liquid.
      (3) Liquid vs. liquid.
      } Instruments classified also by utilization of effects, modes of conversion of energy, thermoelectricity, etc.
   c. Effects at a distance ("radiometry," "radiational pyrometry," "optical pyrometry").
      (1) Methods utilizing Stefan-Boltzmann fourth-power law.
      (2) Methods utilizing displacement of maximum energy density. (Color temperatures, of stars, etc.)
      (3) Methods utilizing selected band or effective wave-length.
         (a) Measurement of the monochromatic energy by visual matching.
         (b) Measurement by "extinction" methods, etc. etc.
         (c) Combinations of (a) and (b).
         (a) Selection by filtration as in use of red glass.
         (b) Selection by spectral curve of receiver, as in use of photocell, film emulsion, etc.
      (4) Methods utilizing the ratio of energy at two effective wave-lengths. ("Two-color pyrometry.")
         (a), (b), etc.: Further subdivision into visual and autometric; then by types of electrical ratio instruments, etc.
      (5) Spectroscopic, spectrographic or spectrometric methods.
      Etc.

III. Methods Utilizing Irreversible Effects

1. *Fusion.*
2. *Color change.*

Etc.

IV. Combination and Miscellaneous Methods

TABLE II
INDUSTRIAL CLASSIFICATION OF TEMPERATURE MEASURING INSTRUMENTS

(Range limits in degrees Fahrenheit)

I. "Thermometers"

1. *Liquid-in-glass (Visible-column)*
   a. Mercury—customary types (–40-950)
      (1) Industrial (complete protection)
      (2) Semi-industrial (incl. special-purpose)
      (3) Miscellaneous (pocket, wall, etc.)
      (4) Etched-stem ("laboratory," "chemical," "testing")
      (5) Enclosed-scale
   b. Mercury—special glass (–40-1200)
   c. Alcohol (–80-150)
   d. Toluol (–130-80)
   e. Pentane (–330-80)
   f. Gallium in quartz (90-1830)
2. *Solid expansion*
   a. Metal and refractory (–100-1000)
   b. Bimetal (–100-800)
3. *Pressure-spring*
   a. Mercury (–36-1000)
   b. "Xylene" (–40-750)
   c. Vapor-pressure (–20-700)
   d. Gas (–230-1000)
4. *Electrical Resistance*
   a. Platinum (–290-2000)
   b. Nickel, etc. (–290-450)

From an industrial viewpoint, the resistance, thermoelectric and radiation – converter types of measuring elements all belong to the electrical-instrumentation category.

II. "Pyrometers"

1. *Thermoelectric*
   a. Rare-metals (32-2550)
   b. Special alloys (–400-1800)
   c. C-SiC (300-3200)
2. *Total-radiation (950 up)*
   a. "Hand"
   b. Autometric, autographic, etc.
3. *Selective-radiation (1200 up)*
   a. Visual
      (1) Brightness matching
      (2) Spectroscopic
   b. Autometric, autographic, etc.
4. *Fusion (1100-3660)*

The "Accuracy" and Other Measuring Properties of Temperature Instruments

By M. F. BEHAR

1. Introductory Comparisons

In special meets for expert riflemen the rules of one event call for measuring the actual distribution of shots on a blank target. No one ever makes a perfect score because perfection then means all bullets (after the first) passing through the hole made by the first bullet, without enlarging it.

Temperature measurement and control is not like that.

In ordinary target practice a perfect score is credited to any rifleman who has not missed the bull's eye. One man may have distributed his shots all over the black circle, another may have shot a pin-wheel group, but both men made a possible.

Temperature measurement and control is like that.

In target practice the size of the bull's eye varies: it is the size of a half-dollar for a short indoor range, up to a three-foot circle at the 1000-yard range.

In temperature measurement the size of the bull's eye, likewise, is roughly proportional to the "distance"—in two ways: (1) Officially, the sizes are prescribed by the numbers of significant figures in the regions of the International Temperature Scale. Thus, anyone who measures the temperature of liquid steel to one degree gets a perfect score because the bull's eye for that range is 1°C. (2) Practically, the sizes grow bigger as we measure the temperature of remote objects. Thus, anyone who measures the temperature of a single small gear blank, in the middle of a batch going through a long continuous furnace, ought to be satisfied with a 5°F. bull's eye, for the errors average that figure.

In Instrumentation, the word error is used in two ways: One refers to errors of observation, for which the instrument might not be blamed. The other refers to causes of instrument inaccuracy; examples "lead error" and "tube error." When a measurement is not autographic, however, there can be no sharp dividing line between the two meanings: for example a parallax error is an error of observation which usually occurs because the indicating element and the scale are imperfectly correlated.

As a rule, however, "the error" simply means the difference between the value indicated or recorded by an instrument and the "true value." In short, it means the *I*Naccuracy. Now we come to the word accuracy, and go on with a formal treatment.

2. Measuring Properties of Temperature Indicating Instruments

Accuracy. Since there is no such thing as absolute accuracy in the instrumental measurement of magnitudes such as temperature, and since the function of a measuring instrument is to assign to a measured magnitude a numerical value, i.e., a mathematically-usable quantity, it follows that "accuracy" is the relation between the true value (of the magnitude) and the obtained value (of the quantity). The true value, of course, is a quantity obtained by means of a "more accurate" instrument which has been certified by means of "still more accurate" instruments defining the International Temperature Scale.

Accuracy as defined in the foregoing is the accuracy of an instrument at only one point on its full scale, as determined by comparison against a standard. It is termed the *Point Accuracy.* It is not the important property known as *Intrinsic Accuracy,* defined as the extent or closeness to which the readings (note the plural) of the instrument approach the true values. The adjective "intrinsic" is necessarily used here to denote the accuracy of which the instrument is capable, not its variable accuracy under unpredictable service conditions. Intrinsic accuracy implies other measuring properties, because its determination involves a more or less complete calibration, in the course of which it may be found that the error varies not only for different true values but for the same true value when successive measurements are made.

Thus, the intrinsic accuracy of an instrument is the resultant of its measuring properties. It usually is expressed in terms of the *limit of error,* defined by the Scientific Apparatus Makers of America as "the maximum error by which the readings of an instrument will depart from true values." This limit of error, in turn, may be expressed in three different ways: (1) its value at a given point, or in a given region of the scale; (2) its ratio to the true value above absolute zero; (3) its percentage of the scale range. This third way is preferable for the majority of industrial temperature instruments with uniformly-graduated scales.

Precision is a term oftener applied to methods and conditions of measurement than to a measuring property and is not to be confused with accuracy or with sensitivity. As a measuring property, precision may be defined as that combination of design factors of an instrument which makes it applicable to fine measurements. The degree of precision is a measuring property. It is usually determinable by visual examination. Therein precision usually differs from accuracy and sensitivity which must be tested for. Precision is a comparative term, akin to "refinement." No sharp boundary line separates "instruments of precision" from other measuring instruments. Relatively speaking, we may say that a precision instrument is one that has a long scale for a short range.

Sensitivity. This important property is broadly defined as the response of an instrument to changes in temperature. The intrinsic sensitivity of an instrument (with which we are dealing) is not to be confused with its sensitivity under conditions of use that can readily be controlled by the user.

The sensitivity of any temperature measuring instrument is the *response* of its indicating element to changes in the temperature it is measuring. (Response to other temperatures is something else!)

The sensitivity of an *industrial* temperature indicating instrument is the readily observable displacement of its indicating element caused by changes in the measured temperature.

Unit Sensitivity is the value in degrees and decimal fractions (generally C.) which will cause a change of (1) one milliradian or (2) one scale division or (3) one millimeter, on the scale of the instrument—depending on the field of measurement concerned.

Ultimate Sensitivity is the value of the change in the measured temperature which will cause effective motion of the indicating element of the instrument.

Note in the definitions: "which *will* cause" displacement of the indicating element. Sensitivity is a property that only shows up in the actual performance of an instrument.

The measuring property which corresponds to unit sensitivity but which can be determined by visual examination, is the *degree of precision.* As to ultimate sensitivity, it has no analogous passive measuring property.

Sensitivity is impaired by "sticking" but not by true lag. It is impaired by frictional damping but not by molecular damping or viscous damping.

Ultimate sensitivity usually varies slightly from point to point throughout the range of an instrument with a uniform scale; it varies considerably throughout the range of any instrument with a non-uniform scale.

There can be no accuracy without sensitivity but the two should not be confused. It is common to speak of a resist-

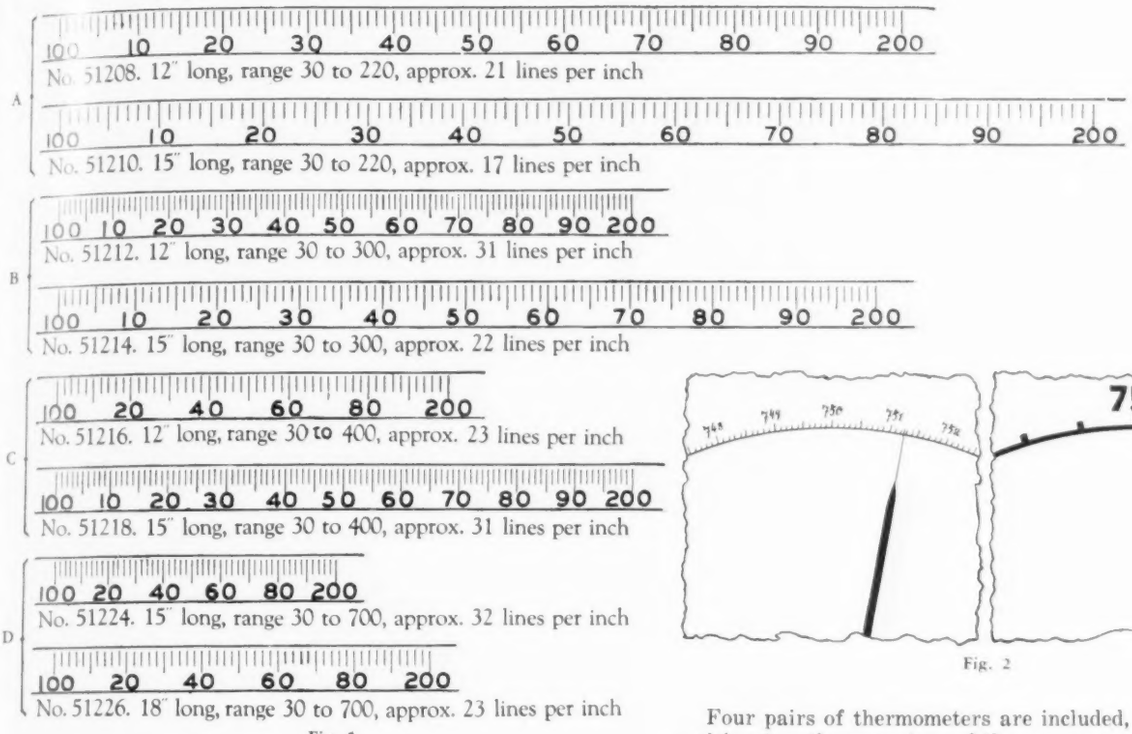


Fig. 1.

ance thermometer, for instance, as "sensitive to 0.01°F." This is a correct expression of its sensitivity, implying that such a thermometer, if it be properly calibrated and if it be free from lost motion, etc., can be "accurate to plus or minus 0.01°F." If sticking should develop, so that the ultimate sensitivity will be 1°F., the thermometer could not possibly be accurate to a fraction of 1°F. On the other hand, an instrument may be extremely sensitive and yet be inaccurate. Examples, a bent pointer, a scale replaced in wrong position after being removed for cleaning, a change in the circuit resistance of an electrical deflection instrument, a weakened spring, etc. The most sensitive widely-used instrument is the galvanometer; and laboratory workers are in position to tell their industrial colleagues that ultra-high-sensitivity galvanometers generally suffer from zero drift, periods longer than 10 seconds, and other troubles.

Scale Law. This fundamental measuring property, influencing other measuring properties in the various regions of an instrument's range, is broadly defined as the manner in which the length of one scale division, always representing the same increment, varies along the scale. This law depends upon (1) the accepted mathematical law expressing the utilized effect; (2) the manner in which the intensity of the utilized effect varies, and with it of course the actual driving force tending to displace the indicating element; (3) the manner in which the direction and intensity of the restoring force vary at the same time; (4) the resultant of other geometrical and physical factors peculiar to the design and construction of the measuring system.

Readability. This is a combination of (1) general factors such as size of instrument; length of scale; length, width, and sharpness of scale divisions; size and legibility of graduation figures; visibility of indicating element; absence of eye-confusing markings or reflections, etc., and (2) specific factors such as minimization of parallax effect in certain forms of indicators. Readability is not only a useful general characteristic but a most important measuring property of an industrial instrument.

A study of Fig. 1 will bring out clear concepts of passive measuring properties such as "Unit Sensitivity" and "Degree of Precision." Portions of the scales of eight total-immersion chemical thermometers* are shown in their actual size. In each case, only the portion from 100 to 200° is shown.

*C. J. Tagliabue Mfg. Co.

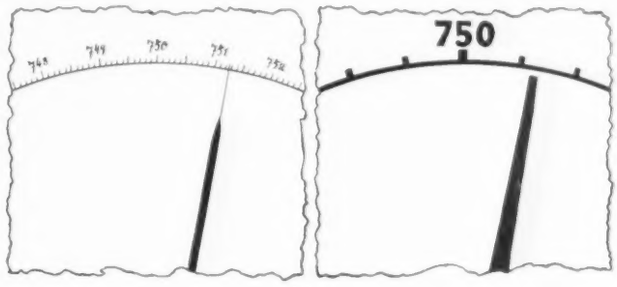


Fig. 2

Four pairs of thermometers are included, each pair comprising two thermometers of the same range and otherwise alike except that the upper thermometer is 12″ long and the lower thermometer 15″ long overall.

This drawing can be used, therefore, as if it showed the scales of eight *measuring instruments of any class or form*, all scaled from "100" to "200" and differing only in scale length and in the consequent necessity for dividing the shorter scales into 2° graduations while 1° divisions are used on the longer scales.

Note that in each of the four pairs, the longer instrument possesses a greater degree of precision. This is especially noticeable in pair "C," where the 12″ thermometer is graduated in two-degree divisions and the 15″ instrument in single degrees. The length of the 100° interval of the latter is 49% greater than the length of the 100° interval of the former, but since it is divided in degrees it can conveniently be read to half-degrees whereas No. 51216 can only be read conveniently to degrees.

Compare also the four 12″ thermometers with one another and then do the same for the four 15″ thermometers: As the range of an instrument is increased without increasing its size, its degree of precision diminishes in proportion. The ranges cover respectively: (A) 190, (B) 270, (C) 370 and (D) 670 degrees. Note the approximate equality of the 100° scale portion of the following:

12″ thermometer with 190° scale and 15″ thermometer with 270° scale.
12″ thermometer with 270° scale and 15″ thermometer with 370° scale.
12″ thermometer with 370° scale and 15″ thermometer with 670° scale.

Fig. 2 brings out the passive properties just discussed, and "Readability." It represents portions of two dial form instruments of identical size and range (which might be an imported aneroid barometer at the left and a made-in-U.S.A. power-plant barometer at the right). This slide always provokes interesting discussions. The imported instrument would seem to be "more accurate" but only an actual test of the active property known as accuracy would disclose the answer. However, the test conditions should be such that the imported instrument would not be graded "A" unless its errors were commensurate with its degree of precision.

Sticking is the term which denotes that the indicating element does not move without an appreciable change in the utilized effect. This term may also be used to designate the amount of effect required to cause motion of the indicating element, in which case it is expressed as ultimate sensitivity.

Lag is a term denoting slowness of response of the indicating element, without implying, however, that the indicating mechanism sticks. The "slowness" is relative; a sluggish oscillograph would be considered a rapidly-responsive recording thermometer. True lag follows a logarithmic-decrement law. It is caused by phenomena such as heat transfer at the measuring element — not by indicating-mechanism friction—and is commonly known as thermometric lag." "Damping lag," on the other hand, is artificially introduced in the indicating mechanism. It may be almost exactly "thermometric," with its curve closely logarithmic, when it is molecular and not excessive but it generally has nothing to do with the "true lag" of the primary element. True lag can be altered by changing portions of the measuring system; damping lag, by modifying the damping means which affects the indicating mechanism (or by replacing such damping means when detachable.)

Damping is that property which minimizes the time required by the indicating element to come to rest at a new value after a sudden change, but without affecting accuracy. In temperature measurement practice this property is of importance chiefly in the measurement of temperatures of moving objects. When the pointer (or other indicator, or pen) of an instrument swings beyond the final reading and comes to rest only after a series of oscillations, the instrument is said to be "underdamped"; and it is said to be "overdamped" when the indicator approaches the final reading, without actually passing that point, in a period of time capable of being reduced. In general it is desirable to have the movement slightly underdamped, in order that its free swing may give assurance of freedom from friction or sticking. For recorders, the damping requirements vary with the "speed" and other desired characteristics.

"Critical damping" is that obtained when reducing the amount of damping would result in oscillations and increasing it would increase the lag. A "dead-beat" movement is critically damped.

Damping lag is seldom objectionable in indicators. In recorders it may be objectionable when the record must show transients; in controllers it is a factor seriously affecting the mode of control.

3. Measuring Properties of Temperature Recording Instruments

Although the foregoing discussion applied specifically to indicators, much of it applies also to the great majority of recorders. It applies especially to direct-acting recorders.

An ideally accurate recording instrument would produce a curve of all successive instantaneous values, say the temperatures along the edge of a strip being rolled at mile-a-minute speed in a steel mill. Even in the recording of slowly changing values there are practical limits to the attainable accuracy of an industrial recorder. First comes the necessity for a record which can be read easily. A thick record may be a wide blur extending from the minimum values to the maximum values, whereas a thin record will show the details. Not only is it frequently desirable to be able to study such details but it always is desirable to know the mean value, which may differ widely from the average value. See Fig. 3. Even where the recorded temperature is fairly constant, a thin record is preferable, but such precision may sometimes be really detrimental, as when it would give a misleading appearance of four-figure accuracy on the chart of an instrument that is only accurate to 2% or so of its scale range.

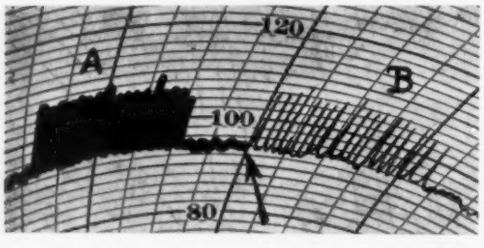


Fig. 3. Average temperature (A) seemed to be 100; after cleaning pen (arrow) it turned out to be 95.

Another limit not only to accuracy but also to precision, is the problem of utilizing a weak actuating force. One solution is to choose a measuring element of a form which provides the greatest mechanical force in proportion to the energy expended. Another solution is to make the pen-arm of the measuring element both long enough to swing over a wide chart scale and light in weight, and to use to external source of power to press the tip of the pen-arm at regular intervals. Another solution is to use a large-size measuring element having a relatively short pen-arm. Another solution is to do away with a pen-arm and have the measuring element command the writing mechanism without any drag at all, through a relay, a servo-motor doing the actual work of inking or printing the curve on as wide a chart as may be desired. This permits the use of extremely sensitive measuring elements and the employment of null methods in self-balancing bridges and potentiometers.

At one extreme we have utmost simplicity, with sources of error reduced in number and minimized in effect (their abolition is impossible); at the other we have total elimination of drag on the measuring element, with a relatively great number of interacting kinematic elements—clutches, gears, pulleys, ratchets, etc. Comparisons between direct-writing and relay type recorders may be made on these facts, but the relative merits of the two classes as temperature measuring instruments depend on many other items, most of which are peculiar to individual designs. Both classes will continue to be in demand.

As a rule, direct writing recorders may be inspected and tested individually *and also compared with one another* in the light of such properties an sensitivity, etc., as discussed in Section 2; but when it comes to indirect writing recorders, while *Accuracy and Sensitivity* retain their meanings, "sticking," "damping," "lag" and other considerations take on specific meanings descriptive of operating characteristics rather than of measuring properties.

Multiple-pen Recorders. Two or more pens can follow the same time line on a chart, but only when each covers a separate portion of the scale. When it is desired that the pens can cross one another—as is usually the case—only one pen can be synchronized with the moving chart; the others are ahead of time or behind time. The closeness of the pen or stylus points to one another depends on their design: finely tapering points can follow the same time line so closely that the lack of synchronism is hardly noticeable; others cannot be made to write closer than 3/32" without interfering. With strip charts the time difference is constant over the scale; with round charts it is least at the outer edge and greatest at the inner edge.

Hygroscopic Effects. Paper is a hygroscopic material. The consequent errors are proportional to three factors: (a) the distance of the record line from the fixed point of the chart (the center of a round chart or the guiding edge of a strip chart); (b) the hygroscopic cofficient of the paper, and (c) the difference between the relative humidity of the air in which the chart was printed and that of the air at the location where the record is made.

For a chart printed on a good grade of paper a fairly but not uncommonly low humidity (15%) and used at fairly but not uncommonly high humidity (80%) the error at the edge amounts to as much as 3% of the scale range. Considering the fact that some industrial temperature recorders are capable of accuracy to 0.25% of the scale range, the hygroscopic error is to be considered.

All reputable instrument firms specify "non-hygroscopic" ledger, bond or parchment stocks, but this only reduces the effect without nullifying it. Some firms print their own charts in air-conditioned rooms at 50% relative humidity (or so instruct their chart printers) and this makes the hygroscopic error negligible on most industrial applications, except of course in midsummer and midwinter. In plants where some recorders are exposed either to nearly dry to to nearly saturated air, the humidity of which is constant, a constant correction can be applied, the value of which can be obtained from the instrument manufacturer. In 1931 there was introduced a full-compensating device consisting essentially of a strip of the same paper as used for the chart, located near the chart and acting automatically on a corrective mechanism.

Off-register Printing and Punching. It is not amiss to sound a warning against charts that are manufactured without assurance that the guide perforations are all properly dimensioned and in perfect register with the printing. Most leading makers of recording instruments now supply charts that are printed and perforated in one operation on special presses.

Industrial Thermometry

Mercury-in-glass — Solid-expansion — Pressure-spring — Resistance

(Chapters I-III constitute the three preceding self-contained articles)

By M. F. BEHAR

CHAPTER IV
MERCURY-IN-GLASS THERMOMETERS

1. General Characteristics

The absolutely essential physical parts of a visible-liquid-column thermometer comprise only the tube and the liquid. The tube consists of a large-volume thin-wall *bulb* and of a *stem* with a relatively small-volume *bore*. The stem alone is sometimes called the *tubing*—particularly when it is of special glass tubing different from the bulb. The smaller portion of the liquid, in the bore, is variously known as the *column* or as the *thread*. To prevent spilling and evaporation, the *tip* of the stem is sealed and therefore the body of gas above the top of the liquid thread in the bore becomes a third physical "part" of the instrument. This gas may be the room air that happens to be left there; or it may be a carefully measured quantity of pure inert gas deliberately introduced for various purposes. One of these purposes is to prevent "thread-break" or "column separation." Another is to permit the instrument to be used at temperatures higher than the atmospheric-pressure boiling-point of the liquid. To prevent injuriously excessive pressures when the thread rises and compresses the gas, there usually is an enlargement of the bore at the tip of the stem, so that the larger portion of the body of gas is in this *expansion chamber* or *upper reservoir*.

So much for the essential physical parts. The device does not become a measuring instrument, however, until it is provided with a *scale*. A plain thermometer, as described above, is usually calibrated by immersion (to a standardized depth) in a series of constant-temperature baths numbering from at least two (for the cheapest) to as many as may be called for in the most rigid specifications. At each bath, the worker files a tiny mark on the stem opposite the top of the thread. This operation is known as *pointing*. A five-point thermometer, therefore, is one whose scale is presumably accurate within limits of observation at these five points. Automatic scale-engraving machines, so designed that they can follow the calibration curve of each individual instrument, are used for engraving the scales of thermometers after pointing at three or more temperatures. (For a two-point calibration, naturally, a mathematical machine is not needed: the graduations are merely made uniform.) The residual error is greatest, of course, mid-way between points, but with the uniform-bore tubing available as a result of recent improvements in the glass industry's production machinery, even a two-point instrument with separate scale may be acceptable for some uses around the plant. It cannot be repeated too often that unless the stem itself is marked—even if only at one point—a separate-scale instrument cannot be trusted. Needless to add, the tube and the scale in separate-scale instruments should be securely attached in relation to each other, and the marks on the tube should be so plain that accidental slippage can be detected without using a magnifying glass.

2. Measuring Properties of Particular Interest

Readability. In recent years, the growth of industrial instrumentation has caused to be diffused among all users of instruments a better appreciation of the relative importance of the various measuring properties of instruments. In industrial instrumentation, readability is considered a most important measuring property. Around 1930, only the strictly "industrial" thermometers (described below) were deliberately made readable; since then, a number of other forms of mercury-in-glass thermometers have had their readability greatly improved by various means. The principal means—an old one originating in the industrial field—consists in substituting, for the traditional cylindrical stem, one of approximately triangular cross-section, with a rounded edge facing the observer. This "lens front" magnifies the apparent width of the mercury thread. This method, though a decided improvement, has been supplemented by other arrangements, designed to provide color contrasts because the plain lens front magnifies the bore above the thread as well as the thread itself, so that under certain conditions of illumination it is difficult to "find the top."

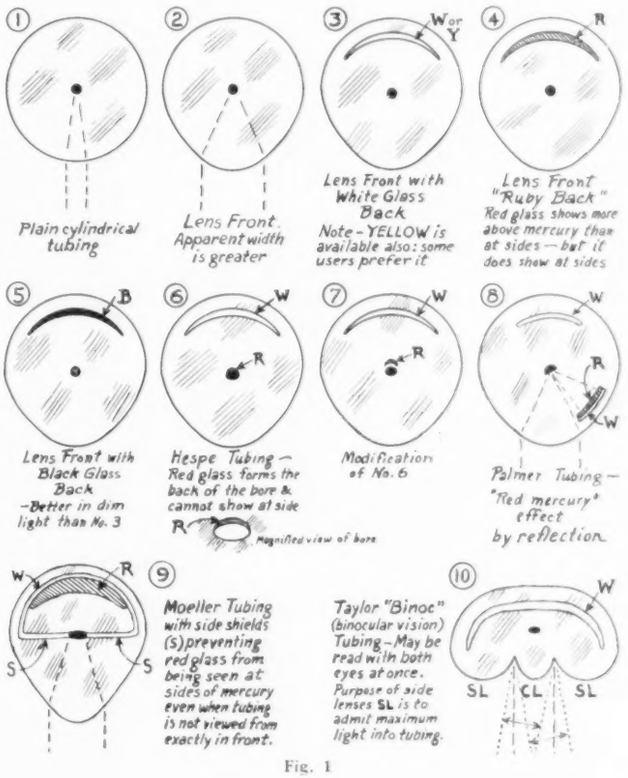

1
Plain cylindrical tubing
2
Lens Front. Apparent width is greater
3
W or Y
Lens Front with White Glass Back
Note - YELLOW is available also: some users prefer it
4
R
Lens Front "Ruby Back"
Red glass shows more above mercury than at sides — but it does show at sides
5
B
Lens Front with Black Glass Back
—Better in dim light than No. 3
6
W
R
Hespe Tubing — Red glass forms the back of the bore & cannot show at side
Magnified view of bore
7
W
R
Modification of No. 6
8
W
R
W
Palmer Tubing — "Red mercury" effect by reflection
9
W
R
S
S
Moeller Tubing with side shields (S) preventing red glass from being seen at sides of mercury even when tubing is not viewed from exactly in front.
10
W
SL
CL
SL
Taylor "Binoc" (binocular vision) Tubing — May be read with both eyes at once. Purpose of side lenses SL is to admit maximum light into tubing.

Fig. 1

The lens front *alone* cannot make mercury as visible as brightly-colored alcohols. Strips of white glass and ruby glass, at the back of the stem, appeared on the market about half a century ago. Since the nineteen-twenties, half a dozen stem constructions affording greater readability have appeared. Fig. 1 is a set of drawings made by the author, in some cases from actual sections of tubings, in other cases from manufacturers' drawings. (The author assumes responsibility for imperfect draftsmanship and imperfect presentation of the advantages of each invention.)

Readability is impaired by "glare." Reflections on the outer surface of the stem (and of the plate-glass front where included) were heretofore considered an unavoidable nuisance, but now they can be minimized (reduced by perhaps 90%) through the application of thin (130- to 140-millimicron) films to the glass surface. Two methods of making "glareless glass" were announced, almost simultaneously, in 1938:

(1) Drs. C. H. Cartwright and A. F. Turner, of the Massachusetts Institute of Technology, evaporate fluorine compounds on the surface of the glass until the desired film thickness is built up, reducing reflectivity (which is approx. 8% in the case of ordinary instrument glass under ordinary conditions) to approx. 0.4%.

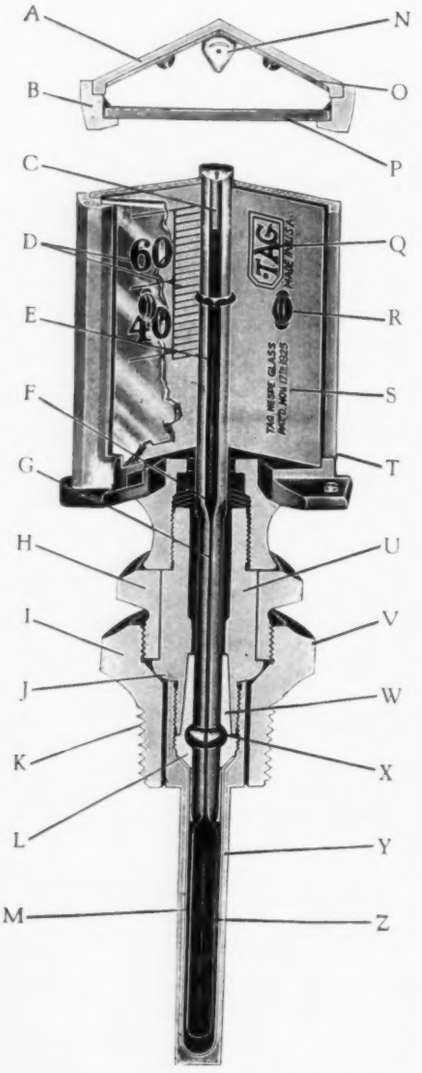


Fig. 2
Construction of a Typical "Industrial" type of Thermometer

A—Scale case.
B—Interchangeable front frame.
C—Gas space above mercury.
E—Mercury.
F—Above this point, the glass has the lens front—as may be seen by comparing the apparent width of the mercury.
G—Cylindrical portion of glass tube, between scale case and bulb, with fine mercury bore to minimize error due to variable immersions. (Important in long-stem portable thermometers.)
H—Coupling nut, revolving freely on stem connecting piece.
I—Union connection hub for attaching thermometer.
J—Seat.
K—U. S. Standard pipe thread.
L—Lower portion of packing seals mercury conducting bath in bulb chamber. Air space between surface of conducting bath and packing allows for bath expansion.
M—Mercury conducting bath.
N—Magnifying lens front tubing.
O—Scales.
P—Plate glass front.
R—Round-headed screws permit removal of scales for cleaning, one at a time and replacing in correct position.
T—Ventilation openings at back prevent glass front from being obscured by condensation of moisture on inside of glass.
U—Connecting piece.
V—Hexagonal wrench head.
W—Asbestos packing.
X—"Blister" formed in the tubing to prevent slipping up or down.
Y—Bulb chamber.
Z—Bulb.
(C. J. Tagliabue Mfg. Co.)

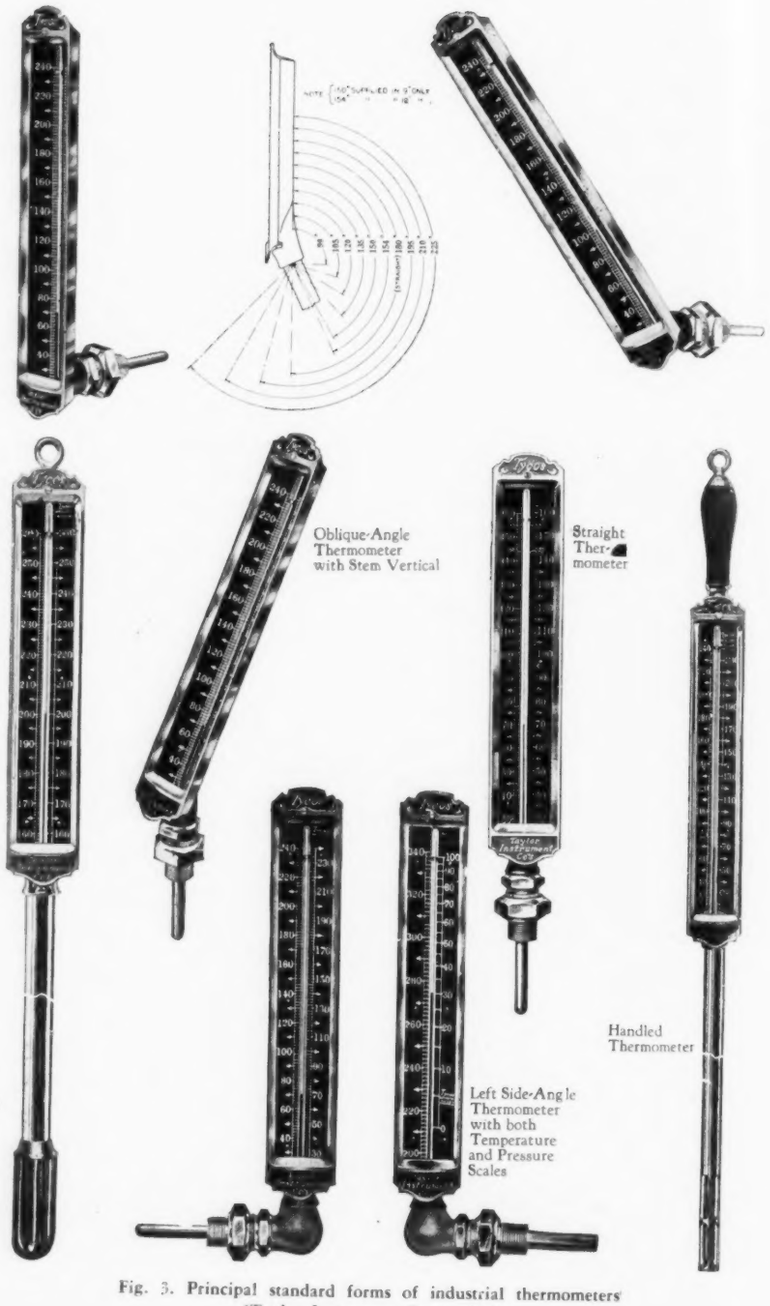

Oblique-Angle Thermometer with Stem Vertical
Straight Thermometer
Handled Thermometer
Left Side-Angle Thermometer with both Temperature and Pressure Scales

Fig. 3. Principal standard forms of industrial thermometers
(Taylor Instrument Companies)

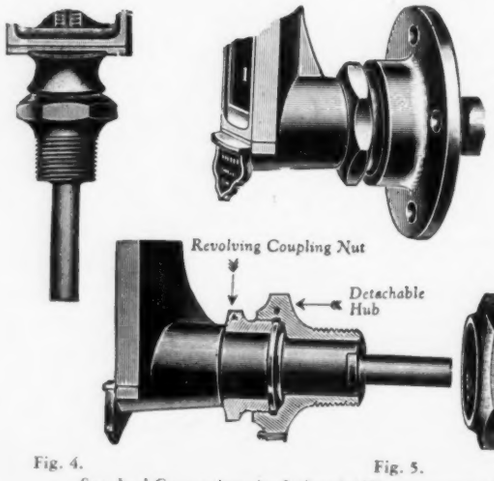


Fig. 4.

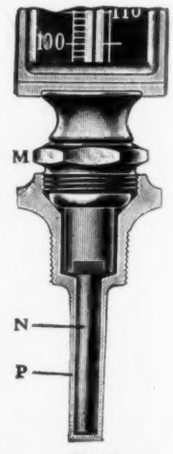


Fig. 5.

Fig. 6.

Standard Connections for Industrial Thermometers. *(C. J. Tagliabue Mfg. Co.)*

(2) Dr. Katharine Blodgett, of the General Electric Co.'s research laboratory, transfers monomolecular films of barium stearate, cadmium arachidate, etc., floating on water, to glass by a dipping technique, the operation being repeated approx. 42 times until the desired thickness is built up, reducing reflectivity to approx. 0.8%. Dr. Blodgett's method is said to permit controlling the chemical composition of the film so that its refractive index will be suited to that of the glass.

At this writing, neither the M.I.T. method nor the G-E method is being offered as an optional feature by thermometer manufacturers, but the probability of early commercialization has dictated that they be mentioned here.

It must be borne in mind that only under monochromatic illumination can either method make glass entirely "invisible." It is impossible to make a quarter-wave-length film eliminate all reflection of all wave-lengths in the visible spectrum because the visible spectrum extends over one octave—red-light waves being twice as long as violet-light waves. Fortunately, the normal eye is many times more sensitive to yellow-green than to red or violet (eighty times more sensitive to $\lambda = 550$ mμ than to $\lambda = 425$ or to $\lambda = 690$) and, moreover, the artificial illumination from most of the modern lamps has its spectral-distribution center of gravity close to that of the I.C.I. Normal Visibility Curve. Each set of workers has, therefore, selected a wave-length close to this center of gravity (the M.I.T., green the G-E, yellow; according to latest reports). Moreover, a film thickness suited to a given visible wave-length is not altogether unsuitable for other visible wave lengths: even a film "calibrated" for a wave-length in the ultra-violet produces a noticeable reduction of glare under full white illumination.

Attainable Precision. Theoretically, with an enormous ratio of bulb volume to bore volume, the only limit of precision—in the sense of "ultimate sensitivity"—would be imposed, in a thermometer of convenient dimensions, say 24", by the difficulty of seeing the top of a filament-like column and by capillarity effects. Practical limitations of size, weight, cost and characteristics of glasses (including fused silica, etc.) create obvious difficulties in the manufacture, calibration and use of theoretically-possible instruments. Considering all these factors—and others mentioned below—it may be said that the practical extreme is around one-hundredth of a degree. This is the least reading for high-grade thermometers manufactured in accordance with the specifications of scientific and technical bodies, for performing standard tests. Since the use of various electrical methods permits the measurement of temperature changes as small as a millionth of a degree, it is obvious that the published agreements and specifications which call for glass thermometers do so because of the relative stability of a self-contained mercury-in-glass instrument. In other words, it is unlikely that a glass thermometer accompanied by a Bureau of Standards Certificate will appreciably change its calibration in weeks or months of careful use.

Stability. There is no such thing as a perfect transparent solid material for making thermometers. In spite of recent improvements in the manufacture of numerous different types of glass, not one combines all desired properties. Many thermometer makers use different types of glass for bulbs, stems and for the connecting tubing between bulb and graduated stem. They also specify different types of glass for different types of thermometers. This diversification has minimized but not eliminated the aging effects. Any piece of glass, even if kept on a shelf, will undergo changes during the years following the month of its manufacture. Therefore, the glass used in high-grade thermometers has been aged either naturally or by some special process. Any piece of glass, when subjected to alternations of relatively high and relatively low temperatures, will undergo changes much more rapid than those of natural aging. Therefore, high-grade thermometers for special purposes are usually subjected to special aging processes whereby the *residual* changes occurring in actual use are minimized.

It goes without saying that the elasticity of the glass from which the bulb is blown is a critically important property. Since the bulb is the very portion which is exposed to temperature changes, exposure of a thermometer to temperatures much higher or much lower than its range limits may undo the good effects of the manufacturer's aging process. Always remember that mechanical or thermal shocks may cause invisible changes (in properties if not in dimensions) which will irremediably impair the accuracy of any glass instrument.

Accuracy. From the viewpoint of the industrial user, readability, precision and stability are the three chief factors contributing to the accuracy of glass thermometers. Progressive manufacturers, therefore, have discarded the forms of accuracy guarantees which were in vogue a generation ago. The trend is away from vague assertions and toward detailed statements in quantitative terms.

Emergent stem corrections and other data on mercurial thermometry will be found in the Appendix.

3. Industrial Thermometers

These widely and importantly used industrial instruments embody the usual glass tube thermometer, but it is completely surrounded and protected by metal and plate glass. The removable plate glass front, framed in aluminum, bronze, or other material, may appear to be a minor item, but it distinguishes those thermometers which really deserve the title of "industrial" from the "oval-back," "open-V" and "miscellaneous" thermometers. Out of more than a hundred thermometer makers in the United States, only a dozen or so manufacture veritable industrial thermometers. Recent decades have witnessed a remarkable development, originally due to A. B. Hohmann, in the mechanical construction of industrial thermometers. In addition to superior mechanical construction, industrial thermometers embody hidden virtues that show up in actual service, and distinguish them further from the "semi-industrial" types. The glass itself meets exacting specifications and the raw tubes are selected with care (we recall seeing a barrel of deliberately smashed rejects in one factory). It is heat-treated to minimize the inevitable deformation and change in properties which glass always undergoes. Bulbs and capillaries are in many cases made of special-composition glass. A dry, inert gas (usually nitrogen) fills the bore above the mercury and prevents thread-break or "separation of column." Each pair of scales is graduated for its tube, which is pointed at several temperatures; and each tube so held that it cannot slip. Mercury of exceptional purity is almost always used as the thermometric liquid, but colored alcohol and other low-range liquids are supplied for applications where the industrial type of thermometer is desired and where temperatures below –40 have to be indicated.

The success of the "Hohmann Type" about a quarter-century ago effected almost a revolution in industries where the word "thermometer" meant something too fragile for plant service. No *essential* change in the mechanical protection has ever been made since then. Fig. 2 is a reproduction of a cut made in 1924 and it remains the author's favorite sectional illustration of an Industrial Thermometer! (The company whose product is shown in Fig. 2 have made further improvements, of course, but the only readily-detected difference between Fig. 2 and the sectional view of their recent models is a refinement in the contours of the surfaces enclosing the asbestos packing.) Various manufacturers have developed various forms of "extra-heavy-duty" and "super-service" mechanical protection. Mention may be made of the Philadelphia Thermometer Co.'s scale-case and front-frame which are fastened together by eight bolts, the joining surfaces being ground flat, the plate-glass being ¼" thick and the whole being dust- and moisture-proof as well as rugged. Various manufacturers have also brought out various forms of heat-insulating sleeves to minimize heat conduction between the scale-case and the parts in contact with the wall of the apparatus or pipe. Recent introduction by the plastics industry of heat-insulating materials of metal-like strength has made it possible to have the benefit of this feature without impairment of ruggedness.

Modern developments in plastics presage also the increasing adoption of these new materials for scale cases, front frames and other major structural parts.

Principal Standard Forms of Industrial Thermometers—The industrial thermometer needs no advocate to defend it from the inroads of other temperature indicating instruments. It must be said, however, that a more widespread acquaintance with the standard forms of industrial thermometers would in many cases make it unnecessary to

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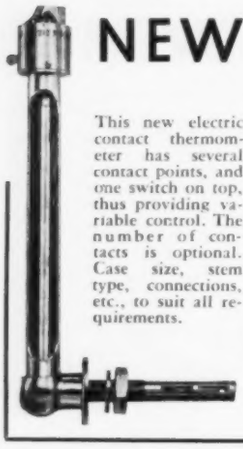
This new form has been designed to be used as both straight and angle thermometer. Five-inch scale; all "regular" stem lengths, ranges and connections.

One of hundreds of "regular" models of engineer type thermometers: 90° (degree) angle, with separable socket. 7", 9" and 12" standard case.



NEW

This new electric contact thermometer has several contact points, and one switch on top, thus providing variable control. The number of contacts is optional. Case size, stem type, connections, etc., to suit all requirements.

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specify another indicating instrument when an industrial thermometer would do as well. It frequently happens that in a manufacturing department where a large number of, say, straight-form short-stem industrial thermometers are giving satisfactory service, the man in charge, forgetting that there are other forms, will order a dial thermometer or electrical resistance thermometer, thereby ending standardization. Fig. 3 shows some of the possibilities of industrial thermometers in this respect. Only a few standard forms are shown. There are many "specials" for various industries —different in appearance but of the modern "industrial" construction whenever that designation is used in the catalog of a reputable maker.

Principal Standard Connections for Industrial Thermometers.

1. *Fixed*—(Fig. 4) This is the simplest style of connection for permanently attaching a thermometer to an apparatus, (a) Fixed Thread—The illustration shows a straight form thermometer with fixed Standard Pipe Thread connection. (b) Fixed Flange—Instead of the wrench head and pipe thread, a fixed flange may be furnished. (c) Pipe Threaded Flanges—When the wall of an apparatus is too thin to enable a thermometer to be securely attached by means of a threaded connection (or when it is necessary to provide a threaded opening at a slant) the thermometer is attached by means of its s. p. t. to a flange, which can be bolted, riveted or sweated to the apparatus. (d) Running Thread and Lock Nut—In this form of connection there is a square shoulder immediately below the wrench head; and the thread is U. S. Standard machine thread (not tapered).

2. *Union*—(Fig. 5) A union connection permits a thermometer to be securely attached without at the same time turning the scale case. The case, therefore, can be faced any direction before tightening the connection. The essential feature is a revolving coupling nut, free to turn on the connecting piece. Its function is to hold the thermometer securely to the fitting (hub or flange) while sealing the opening through which passes the stem of the thermometer. In the lower illustration of Fig. 5 is shown a union *hub*, which has a standard pipe thread on the outside. For thin-walled apparatus, a union connection *flange*, as shown in upper illustration of Fig. 5, is used instead of the hub.

3. *Separable Socket*—(Fig. 6) A separable socket is an additional chamber or well, which exactly fits over the bulb-chamber and stem of the thermometer. It has the advantages of the union connection; and permits also that the thermometer may be removed without creating an opening in the pipe or apparatus. It therefore is used where pressure or vacuum is a factor. For protecting the thermometer itself against corrosive fluids, sockets may be made of special materials: even if they have to be renewed periodically, the thermometer is saved.

4. *Adjustable*—(Fig. 6, bottom) While handle-top and straight form adjustable connection thermometers are all portable, it often is desirable to attach them to a kettle or other apparatus; even if only in order to locate the stem and bulb properly. Hence various clamping devices applied to the plain tubular stem.

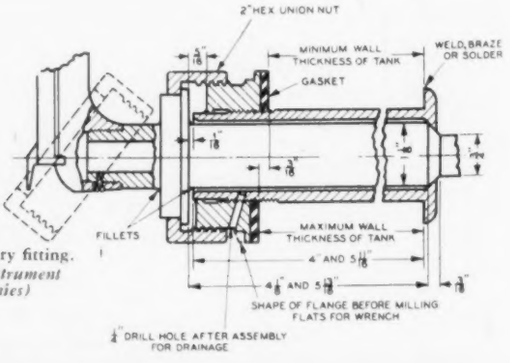
2" HEX UNION NUT
MINIMUM WALL THICKNESS OF TANK
WELD, BRAZE OR SOLDER
GASKET
FILLETS
MAXIMUM WALL THICKNESS OF TANK
4" AND 5"
SHAPE OF FLANGE BEFORE MILLING FLATS FOR WRENCH
DRILL HOLE AFTER ASSEMBLY FOR DRAINAGE

Fig. 7. Sanitary fitting. *(Taylor Instrument Companies)*

For various standardized industrial processes, special connections and fittings have been devised, including ventilated fittings for steam-jackets, wall fittings, etc. Fig. 7 shows

tion arrangement whereby an industrial thermometer may be applied to equipment in the dairy industries in conformity with the rigid requirements of sanitary officials and technical organizations. Thermometers of both the industrial and semi-industrial construction and workmanship may be obtained with various special-industry fittings.

Bare Bulbs—For many applications, particularly where gas temperatures must be measured, the glass bulb should not be enclosed in a bulb chamber because the thermal lag might be objectionably great. For such applications it is well to specify a bare bulb, protected by a suitable guard such as a perforated metal tube of comparatively large diameter. Flanged or s. p. t. union connections are optional Lag is much less than with a bulb chamber, but a pressure-tight connection ordinarily impracticable.

Principal Sizes of Industrial Thermometers—By "size" is meant the length of the pair of scales alongside the visible portion of the tube. The standard scale-length sizes are 7", 9" and 12". The scale cases are between 1½" and 2" longer.

"High Ranges"—Industrial thermometers are listed in catalogs in ranges up to 1000°F. (538°C.) but the bulb chamber construction and other details for ranges above 750°F. are special; there is an extra charge; lag is greater; unavoidable aging effects may necessitate relatively frequent calibration, and when the thermometer is continuously used above 900°F. the destructive effects may soon make the instrument unserviceable. Thermometers of the typical "industrial" construction are not recommended for use above 900°F. Special instruments, variously known as tempering-bath thermometers, type-metal thermometers, flue-gas thermometers, etc., when made with care of selected materials, may be exceptions to this statement.

4. Miscellaneous Thermometers

There are many forms of mercury and spirit thermometers which, without being of "Industrial" mechanical construction and general workmanship, are nevertheless of wide usefulness in all industries. In this category are some special-purpose thermometers of quality equivalent to "Industrial" and differing therefrom in specification details that have no bearing on stability and accuracy. Fig. 8 shows fourteen miscellaneous thermometers of one make and gives an idea of the variety on the market.

5. Etched Stem Thermometers

These instruments, also known as *engraved stem* or *laboratory* or *chemical* or *test* thermometers, while indispensable in the laboratory, cannot be discussed at length here, for their fragility makes them unsuitable for industrial plant service. Provided with closely-fitting or loose cylindrical metal cases they are known as *armored* or *pocket* thermometers and are of great importance in testing. The sensitivity of these thermometers greatly exceeds that of the industrial types and the lag is less, but this is due in part to the greater thinness of the bulbs. The higher grades are instruments of precision.

6. Beckmann Differential Thermometers

If the volume of the expansion chamber or upper reservoir (mentioned at the beginning of this chapter) be made as large as that of the bulb, there will be no danger of overranging a short-range thermometer. The Beckmann type not only employs this idea but is so designed that (1) some mercury can overflow from the top of the bore into this reservoir and stay there; and (2) some mercury can be transferred back by manipulating the instrument. Every time this happens, of course, the range is displaced—which is exactly what the inventor desired that the user should be able to do at will. Beckmann thermometers may be graduated in hundredths of a degree (F. or C.). Their obvious purpose is to measure small (say 2°) temperature changes or temperature differences with a relatively small error—small in percent of this change or difference. Among features of improved designs may be mentioned an auxiliary scale for the upper body of mercury and a "dropping" arrangement whereby each drop of mercury has a rated value in relation to the auxiliary scale. This minimizes the drudgery of "setting" the instrument to the desired correspondence between the mid-point of its scale range and a definite temperature.

Two of Many Specialties

Modified and simplified Beckmann type thermometer recommended for inexperienced laboratory workers and preferred by technicians of long experience. Improved and heavier construction of capillary obviates customary glass case . . . does away with rattling of thin tube . . . Less expensive, too!

New quick-reading thermometer for micro testing. Perfected construction of enclosed porcelain scale assures permanent readability. Long thin bulb speeds up response: this is a three-second thermometer! Available in any range; generally furnished in sets of three: 0-100, 100-200 and 200-300°C. (or equivalent F.). Size approx. 6 inches.

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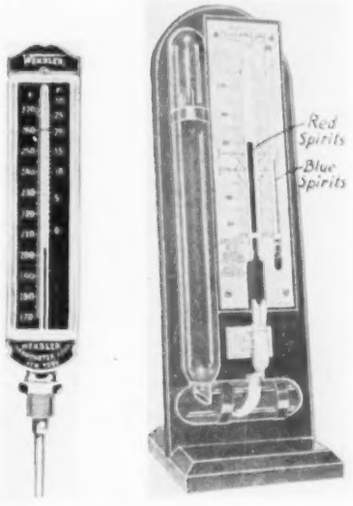

No. 169. For pressure-cooking processes; with 2 scales: 170-270°F. and 0-30 lbs. pressure. Nine-inch scale length.

NEW Bailey-Parsons Thermometer reacting to effects of temperature, humidity and air circulation, providing best guide for air conditions in workrooms, offices, etc.

No. 326. Max. & min. registering thermometer in 12" shelter type copper case. Approx. range minus 40 to 120°F.

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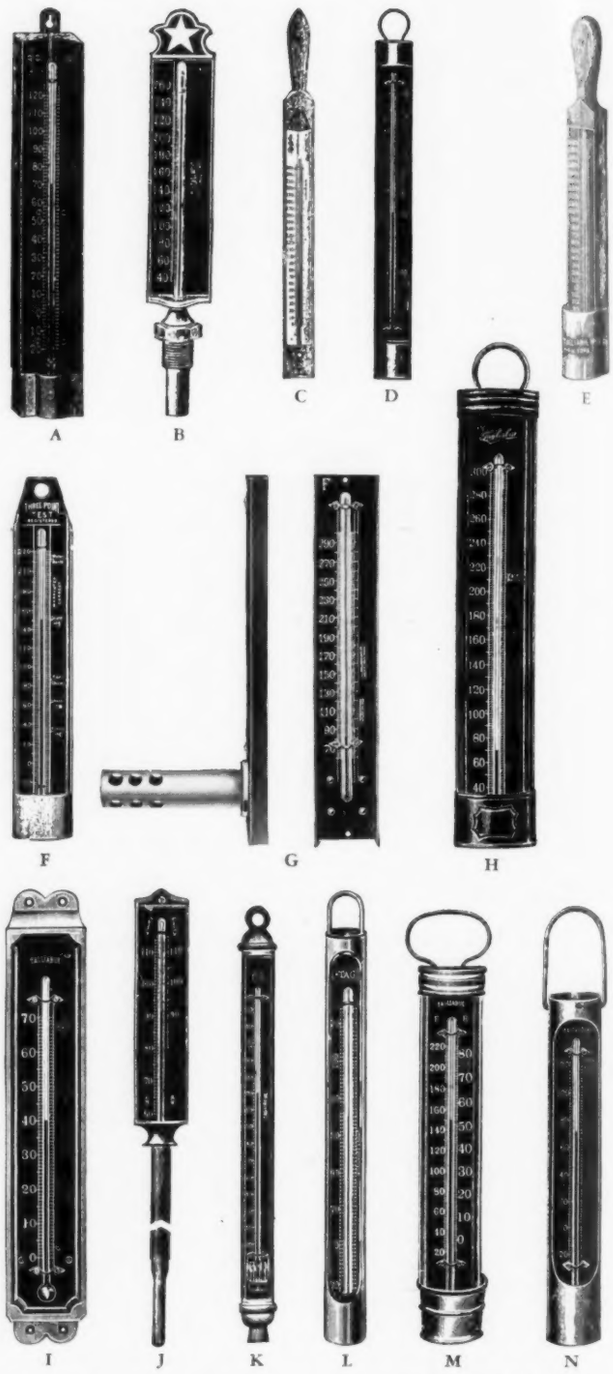

Fig. 8. "Miscellaneous" Thermometers. Some of Semi-Industrial Construction. *(C. J. Tagliabue Mfg. Co.)*

A—Open V shape wood case standard grade thermometer. This is not the kind designated as "floating" but it will float if accidentally let go in a liquid.

B—Nickeled steel case flat back thermometer with ½ inch S.P.T. Not of "industrial" construction but frequently adopted as equipment on quantity-production vats, etc. Also made in angle form.

C—Wood case handled thermometer, 18″ V-shape back.

D—18″ copper case "confectioner's thermometer."

E—Cup case tank thermometer (wood case with brass cup), metal scale.

F—"Flanged" dairy thermometer, 10″ size.

G—"Flanged" angle thermometer of angle form with bare bulb and perforated guard, for air dryers and similar equipment.

Fig. 10. Sanitary-fitting connection for dairy industries. *(Taylor Instrument Companies)*

H—A well-known form of stamped metal case thermometer. Some models for low-temperature work are spirit-filled.

I—A familiar form of wall thermometer. The case is galvanized or enameled iron. The usual size is 12″.

J—Dough-testing thermometer with 7″ open V iron case and 10″ nickeled stem.

K—"Shiphold thermometer." The galvanized iron case has rubber bumpers at sides and at bottom.

L—Cylindrical cup case thermometer with V-shape metal scale.

M—Copper scoop case thermometer, 12-inch size.

N—12″ cup case thermometer, 1¾″ diameter.

7. High-temperature Visible-column Thermometers

Mercury-in-glass thermometers should not, *as a rule*, be used above 850°F. The use of special glasses and glass-like materials, with higher softening points, permits higher *mercury* ranges by permitting the gas to be compressed and the boiling-point of the mercury raised, without injurious effects. The other solution of the problem is to use gallium (boiling-point around 2900°F.) in a tube made of one of these special materials.

Gallium-in-quartz Thermometers — The commercial gallium-in-quartz thermometer when it appears (before the next edition of this book, perhaps?) will probably give as reliable indications at 1800°F. as are given at 950°F. by mercury industrial thermometers with high-pressure nitrogen filling, special bulb glass, special capillary glass and special bulb-chamber construction to prevent erratic changes in bulb volume—features which make them relatively costly.

Quartz is a common mineral of many forms and methods of occurrence. In instruments, it is used raw or natural only for pivot jewels. (Therefore "gallium-in-quartz" is technically incorrect.) Fused quartz, quartz glass, and such quartz materials are importantly used in industrial temperature instruments, for resistance bulbs, thermocouples, mercury thermostat switches, fusion cones, etc. As a matter of fact, natural quartz becomes something else when heated: It inverts to tridymite with a 15% increase in volume at 870°C., and at 1470°C. changes to the ordinary Mexican cristobalite. The gallium thermometer (for which the author predicts a great future when someone offers it to industry) will have to utilize not "quartz" but some industrial quartz product. A material with a softening point of 1750°C. has been produced by the General Electric Co. It would seem that the industrial gallium-in-quartz thermometers will be readily applicable for temperatures up to 1000°C. (1832°F.) The chief difficulty appears to be the resistance of quartz materials to etching. This precludes the early introduction of *laboratory* instruments with scales etched on the stem, but not of *industrial* instruments (with separate scales) the tubes of which are merely marked by small scratches when "pointed." Another difficulty is drawing fused quartz tubes with bores as uniform as those of high-grade glass tubes.

Gallium. The small amount of refined gallium at present available is a real obstacle—that is to say merely a challenge to American ingenuity. (So were aluminum, magnesium and helium costly and "rare" not so long ago. It will be the same story with gallium!)

"*Hyperthermometers*," brought out in 1931, are scaled up to 1200°F. or 650°C. and therefore belong between the usual mercury-in-glass and the gallium-in-quartz thermometers. They are similar to the etched stem instruments in general appearance, the main difference being in the glass which has a softening point. They would seem to meet the requirement for indicating industrial temperatures in the border-zone between 900 and 1200°F.

8. Low-temperature Visible-column Thermometers

Best-remembered numbers in thermometry are 0 and 100; 32, 212 and 180; and also –40 where C. and F. meet and where mercury freezes. (Exact f-p., –38.783°C.) The principal thermometric liquids used for measurements below –40° are:

Liquid	*Customary limits of scale graduations*			
	Lower		Upper	
	°C.	°F.	°C.	°F.
Alcohol	–60	–80	300	150
Toluol	–95	–130	30	80
Pentane	–200	–330	30	80

It may be worth mentioning also that if, instead of pure mercury, a eutectic alloy of 91.5% mercury and 8.5% thallium is used as the thermometric liquid, the lower point of the range can be brought down to –60°C. or –76°F.

CHAPTER V
SOLID EXPANSION THERMOMETERS (BIMETALLIC)

1. Differential Linear Expansion Thermometers

The first industrial devices for measuring temperature by the change of length of a solid were clay cylinders used by Wedgwood in the 18th century. The expansion of platinum was used by Daniell for high-temperature measurement early in the 19th century.

All such devices, of course, utilize the *differential* expansion of two solids, for there must be a "yardstick" which does not change its dimensions as does the thermometric rod. The earliest pyrometers regularly manufactured for industrial use, therefore, consisted of two rods or tubes. At

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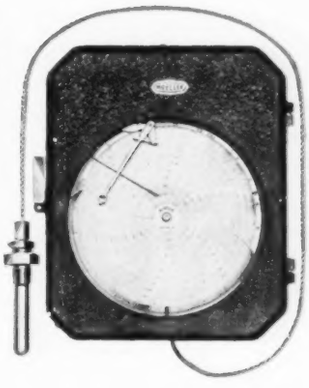

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the furnace end of the device the two materials were attached; at the dial head of the device, the ends of the two rods or tubes were free to move in relation to each other and this motion actuated the pointer. There are on the market some modernized forms several feet in length, the stem consisting of an outer metal tube and of an inner refractory rod; and the dial generally being perpendicular to the axis of the stem.

The expansion coefficients of all known solid materials—even "pure" precious metals—change as a result of repeated cycles of temperature changes. Therefore, such instruments should seldom be used above a dull red heat; and 1000°F. is the usual upper limit for such expansion thermometers or pyrometers in which the tube is made of any kind of iron or steel. Neither can the refractory member be expected to remain an invariable standard of reference! However, one frquently hears an old-timer say that such instruments "settle down" after a few months of being "cured" by actual service, and that after resetting the pointer at the end of such a cure the instrument stays accurate for many years. In the absence of quantitative reports, one may assume that the instruments were found accurate because they were designed to be read to the nearest 10° or so. See Chapter II, Section 2.

Rod-type units cannot be dismissed without mentioning their high "power" as compared with units which deflect. Even allowing for the much smaller travel and for the elasticity of a "rigid" rod, the product of available force times distance is hundreds of times greater for the rods than for the spring-like elements. Since energy is the deciding factor in large (say 12" dial) instruments and in operating valves, the rod element will not soon pass out of the picture.

2. Bimetal Deflection Thermometers

The field of solid expansion thermometers today comprises few metal-and-refractory devices. This field now belongs almost entirely to instruments employing bimetallic elements. The manufacture of these elements has become a special industry in recent years, because of growing demand for simple thermostatic devices produced in enormous quantities for incorporation in household devices. Thus it has come about that the term "bimetallic thermal element" is being supplanted by the name of the product from which such elements are made—which is "thermostatic bimetal."

Thermostatic bimetal is a metallurgical product made from two metals which have widely different temperature coefficients of expansion and which have been firmly bonded at their face of contact. When subjected to a change in temperature, the composite material will change shape, which change of shape is utilized for measurement and control purposes. In addition to having widely different coefficients of expansion, the components must have mechanical properties suitable to minimize hysteresis and provide adequate strength. (For example, lead cannot be used as a component.) The two component metals are usually of equal thickness and firmly joined before being rolled down to size.

The first known application of thermometric bimetals was in balance-wheel compensators, supposed to have been used in 1775 by the great watchmaker Abraham Louis Bréguet, who later invented the *bimetallic spiral thermometer* and whose descendants have been manufacturing these instruments. In 1863 Villarceau published an analysis of thermostatic bimetal in the *Annales de l'Observatoire Impérial de Paris*. With the discovery by C. E. Guillaume in 1898-1899 of the low-expanding alloy known as invar, consisting of 36% nickel and the remainder iron, a new impetus was given the work on bimetals. A number of bimetallic-spiral *indicating* thermometers appeared on the European and American markets. The Bristol Co. probably was the first to bring out a *recorder* of this class, suitable for industrial service. Its element is not a spiral but a helix.

The effectiveness of a given bimetal depends upon the difference in thermal expansivity of the *two* components. Although numerous alloys now on the market have high expansivity, there are only a few alloys with expansivity nil or negative or at any rate sufficiently low for commercial use in bimetals. Moreover, the thermal or mechanical treatment of an invar type alloy changes its expansivity.

When such an alloy has been heated and then slowly cooled, its expansivity rises; but its expansivity falls if the cooling has been rapid. When such an alloy is cold-rolled or drawn, its expansivity will decrease still more. By first quenching and then drawing a rod to the limit, it is possible to reduce the expansivity to such an extent as to reach a negative value. Reheating at 212°F. for several hours brings the value up to substantially zero. In processing invar for bimetal applications, however, advantage is not taken of this property, since reheating to higher temperatures will cause its expansivity to revert to the higher minimum.

Materials for the high-expansion side, in addition to having a high coefficient of expansion, should have good brazing or welding properties, should develop high elastic properties as a result of cold-working, and should have high heat-resisting properties. To meet the requirements for high-temperature, high-deflection bimetals of good constancy, various nickel-chrome alloys have been adopted for the high-expanding side. Developments in high-temperature bimetals have been mainly related to the high-expanding side.

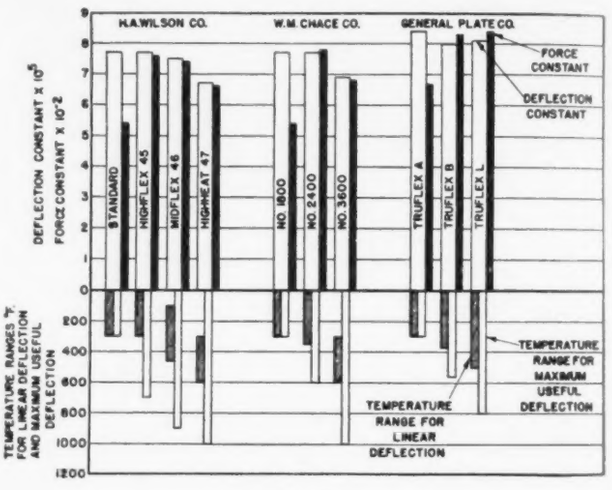

Fig. 1

The important thermal properties of a number of representative bimetals are illustrated in Fig. 1, the data for which were obtained from manufacturers' literature and correlated by Eskin and Fritze.* The bimetals which they selected for this chart characterize the three general groups into which a number of commercially available bimetals may be classified, depending upon the temperature range of applications, low, medium and high. The bimetals selected for this illustration are made by the three largest manufacturers of this material in the United States: W. M. Chace Co., General Plate Co. and H. A. Wilson Co. In the upper part of the figure, deflection and force constants are given. The lower part of the figure shows the temperature ranges for which the deflection is directly proportional to the temtemperature change, and the useful temperature ranges.

So much for the modern product known as thermostatic bimetal, the practical perfecting of which has created a new class of "thermometric substances," so to speak, the possibilities of which are just beginning to be exploited.

Progress in realizing such possibilities depends upon (1) the design of bimetallic members and (2) the design and construction of the co-acting parts of an instrument. Progress along these two lines is well under way, as witnessed by commercial embodiments recently brought out.

Illustrating this principle (the commercial embodiment of modern bimetals, of special design of bimetal elements, and of special design of the rest of the instrument) is the "Temperature Gauge" brought out by the Weston Electrical Instrument Corporation in 1935. The bimetallic element is

*S. G. Eskin and J. R. Fritze, "Thermostatic Bimetals," *Transactions ASME*, Vol. 62, No. 5, July 1940, pages 433-440; discussion pages 440-442. Grateful acknowledgement is hereby made for the help which this disclosure has been in revising this chapter.

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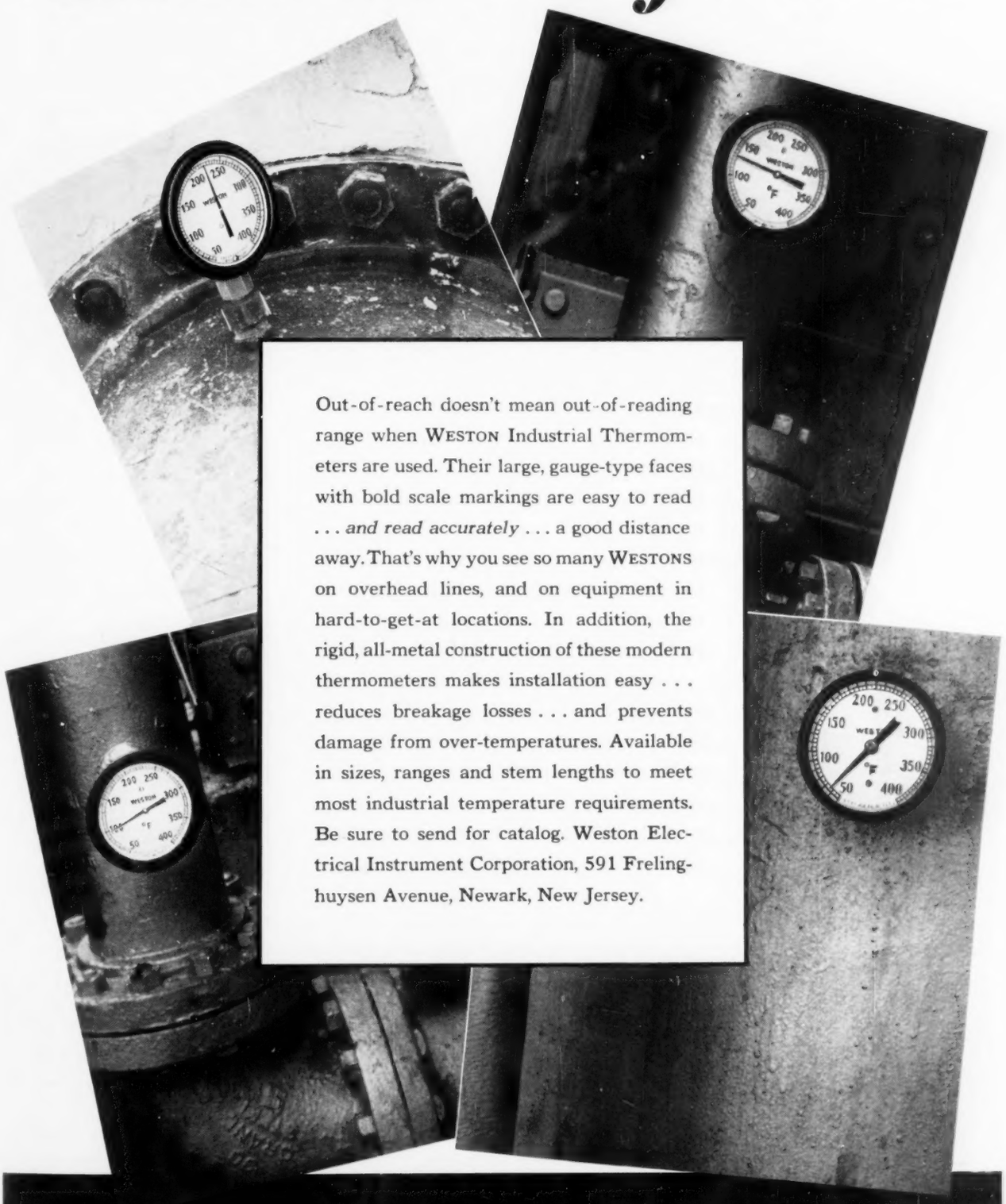

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shown in Fig. 2; a section of one of the smaller-size thermometers is shown in Fig. 3. The following is an abstract (re-worded by the present writer) of a portion of a technical article released by that company in 1935:

"A mathematical analysis by F. G. Bloch recently indicated the improvement in rigidity, accuracy and available torque to be obtained by an element consisting of several concentric helices, so wound that their rotational deflection is additive while their axial displacement is mutually counterbalanced. Development of novel apparatus by which these concentric helical springs may be wound from a *single* strip of bimetal has opened the way to practical utilization

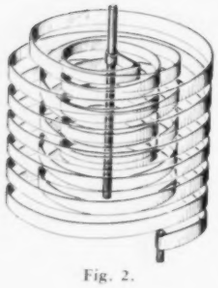


Fig. 2.

Fig. 3.

of this principle in the construction of bimetal thermometers and temperature control devices combining minimal lag, small size and ruggedness. Reduction of strip width and thickness, and the compact form in which the greater strip length is secured, permit the construction of thermometers of sufficient torque to provide deflection of a pointer over a scale long enough to be read to fractions of a degree, with a thermal element as small as the bulb of a glass thermometer."

The bimetallic element used in the Weston thermometers is being produced today in several sizes, for a line of indicating thermometers with dials from 1½" to 6" in diameter. In addition to the pipe thread connection shown in Fig. 3, there are available separable sockets and other accessories, the number of which is of course smaller than in the field of industrial mercury-in-glass thermometers, but growing.

The structural design of the great majority of bimetal elements is such as to produce a deflection—generally a rotation. In many applications, requirements of kinematic design call for a straight-line effect, exactly as obtained from the 19th-century rod pyrometers and rod thermometers. A solution of the problem of obtaining this linear expansion and contraction from the bimetal element has recently been announced by the General Plate Co. In the manufacture of this novel unit, the narrow (approx. ⅛") bimetal ribbon is wound in the form of a coil having the same outside diameter as the ribbon itself. The appearance of the helix at this stage is like that of a "spiral-wound" flexible armored cable. The next stage is to take a long length of this narrow coil, say 30 inches, and coil it into a helix which has an outside diameter of approx. ¾" but which is only approx. 2½" long. The final result of this process is a unit which has the property of expanding and contracting in a straight line coinciding with its own longitudinal axis. These General Plate Co. units are used only in temperature *control* devices at this writing.

CHAPTER VI
PRESSURE-SPRING THERMOMETERS

1. General Characteristics

Pressure-spring thermometers ordinarily embody a "tube system" consisting of (1) a primary element in the form of a bulb, (2) a flexible capillary connecting tube and (3) a hollow pressure-responsive spring which moves the pointer or pen-arm (or which actuates the pilot or relay in a controller). Therefore they are sometimes referred to as "metal bulb and capillary tube" thermometers, or even as "pressure gage" thermometers. The system contains a thermometric liquid or gas. The utilized temperature effect of this substance is always a pressure effect—even when its thermometric property is expansivity.

The universally accepted classification of pressure-spring thermometers is by the "filling" of the tube system. The original scheme (still used in some cases) was into three numbered classes. The usual engineering designation of these three classes has been "liquid expansion," "vapor-pressure" and "gas-filled." Without aiming to overthrow this classification into three classes, the author pointed out in 1930 the usefulness of recognizing that there are four classes. His reason—as valid now as in 1930—is as follows: The vapor-pressure systems and the gas-filled systems may each be conveniently described and studied as a class; but the "liquid expansion class" is different: with regard to applications, characteristics, limitations, etc., it really consists of two sub-classes, (a) mercury, and (b) liquids other than mercury. Such liquids *may* be various hydrocarbons, but xylene* has for some twenty years been used in 90% of the non-mercury liquid-expansion instruments in industrial use. The characteristics of the mercury instruments are so different from those of the xylene instruments that in undertaking to describe and tabulate the industrially-interesting characteristics of pressure-spring thermometers it was found necessary to split up the old "Class I" and to publish the new "rational" division into four classes:

Mercury	Vapor-pressure
Xylene	Gas

The fundamental operating principle employed in all four classes is the measurement of a pressure effect, by means of a pressure-responsive device. This device is unsuitable for ordinary volumetric measurements but its form is such that its internal volume increases as it uncoils. Therefore the entire system is not a constant-volume system.

The principal characteristics of the four classes are set forth briefly in Table III. Numbered notes pertaining to this table are added for the sake of amplification and clarification. These data are believed to satisfy all quick-reference requirements.

Outside of this table and the set of notes, however, a few general and specific statements remain to be made.

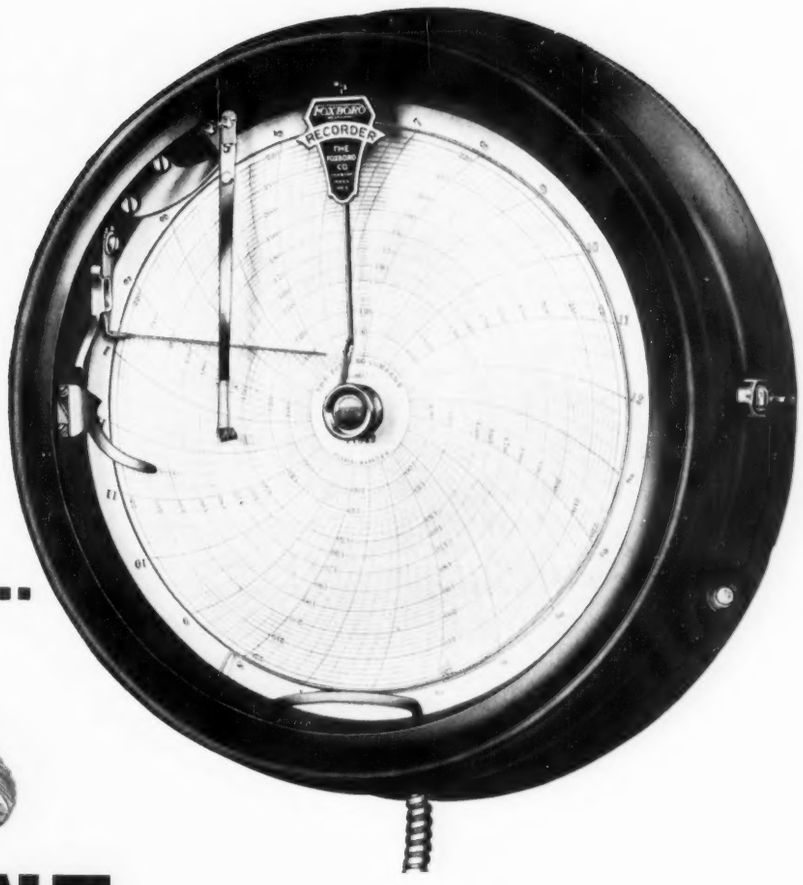
Pressure-spring thermometers possess one obvious advantage over the "industrial" and bimetallic thermometers which are local instruments: However inaccessible the point of application of the bulb may be (within tube-length limits), the "instrument" proper may be installed at eye-level.

It is worth noting that one industry, comprising thousands of small establishments many of which are owned by persons of foreign birth, refused to buy "industrial" thermometers, used cheap thermometers, or did without any, until it was awakened in the 1920's to the business value of dial thermometers easily read by workers and seen by customers. This industry then began buying pressure-spring dial thermometers. Today it does not have to buy them separately, for modern temperature instruments come with all major units of processing equipment for that field.

Pressure-spring indicating instruments (dial thermometers) ordinarily are made up with one tube-system and one pointer; some may be made up with two pointers co-axial like the hands of a clock. Recorders are frequently made up with two tube-systems, sometimes with three or four. Most controllers are single-system, but dual system or duplex controllers are regularly made up by several companies.

Centralization (Fig. 1) is made possible, for capillaries may be as long as 100 feet or more. Electrical instruments

*Usually meta-xylene or dimethyl-benzene-*m.*, $C_6H_4(CH_3)_2$; freezing-point —54°C., boiling-point 139°C. at N.B.P.



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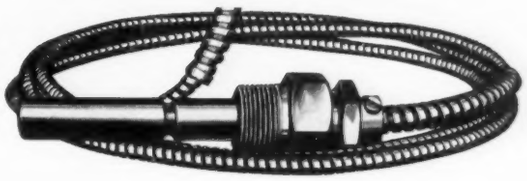

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TABLE III—CHARACTERISTICS OF CLASSES OF PRESSURE SPRING THERMOMETERS

Class	MERCURY	"XYLENE"	VAPOR-PRESSURE	GAS
Filling	Mercury under initial high pressure (Note 1)	Xylene under moderate initial pressure	Volatile Liquid (Note 10)	Inert gas under moderate pressure
Scale	Uniform	Uniform to 250°F., progressive above (Note 5)	Progressive (Note 11)	Uniform
Bulb Volume	Medium, and varies inversely with length of range	Small (Note 6)	Small (Note 12)	Large, and varies with *Tube* length
Minimum Bulb Length	3 to 5 inches	1 inch	2 inches	6 inches
Material	Steel	Brass, Monel or nickel	Brass, Monel, steel, etc.	Brass, Monel, steel, etc.
Maximum Tube Length	25 feet (Note 2)	75 feet when uncompensated	250 feet (Note 12)	150 feet (Note 16)
"Speed"	"Good"	"Good"	Mostly "excellent"	Mostly "low"
Effects of temperature fluctuations along the capillary ("Tube error")	Vary with tube length and with area of capillary bore (Note 3)	Vary with tube length (Note 7)	None as long as bulb is hotter than tube (Note 13)	Vary with tube length and inversely with bulb volume (Note 17)
Can temperature fluctuations at spring be compensated	Yes	Yes (Note 8)	Compensation unnecessary (Note 13)	Yes
Effects of variations in atmospheric pressure (also "Altitude error")	Small (negligible in systems filled at high pressure)	Extremely small	Slight errors in lower end of range where actuating pressure is low	Slight errors at low working pressure only
Does different level of bulb and head affect calibration?	Yes—(Note 4)	Yes—slightly (Note 9)	Yes (Note 14)	No
Lower limits of ranges	—38°C. or —36°F.	—40°C. or F.	—30°C. or —22°F. (Note 15)	—150°C. or —230°F.
Upper limits of ranges	538°C. or 1000°F.	400°C. or 750°F.	371°C. or 700°F. (Note 15)	538°C. or 1000°F.
Usual maximum commercial length of range	538°C. or 1000°F.	333°C. or 600°F.	140°C. or 250°F. (Note 15)	550°C. or 810°F.
Usual minimum commercial length of range	25°C. or 45°F.	22°C. or 40°F.	50°C. or 90°F. (Note 15)	50°C. or 90°F.

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NOTES

(General Note)—Table III had to be compiled, in part, from information released for the first time by various qualified sources. In some cases the author merely put down, from experience, the briefest possible answers to the questions in the first column.

(1)—Comparative advantages of the high-pressure mercury filling are ruggedness, durability and permanent accuracy. It requires the use of steel, for mercury would amalgamate with other common metals. A slight disadvantage is that bulb must often be protected to resist corrosive conditions. This increases the lag, and may cause heat-conduction error. Whenever there is room, long sockets should be specified.

(2)—150 feet or more when a method of "full compensation" is used. One method uses a double connecting tube: inner capillary performs usual function; gas-filled space between actuates a second pressure-spring, shifting the mercury mechanism to compensate for temperature fluctuations along the tube. In another method, the capillary tube is of high-expansion material, and has running throughout its length a wire of low-expansion material, so that for a given change in temperature, the change in mercury volume is the same as that of the annular space it can occupy. A third method uses a gas-filled capillary alongside the mercury capillary, this body of gas actuating a second pressure-spring as in Method One.

(3)—No effects when "full compensation" method is embodied in the system.

(4)—13.6 times the hydrostatic pressure of water (about 15 times that of hydrocarbons) for the same altitude difference, but mercury systems being filled at higher pressure, net effect is *not* 15 times greater than for xylene.

(5)—Non-linearity above 250°F. is slight and it is said to be the same in successive shipments of xylene accepted for fillings; therefore, printed recorder charts may be used.

(6)—But not as a cursory cubing would lead one to believe. In other words, for bulb *lengths* of 1", 2", 3" and 6", volumes are not in ratio of 1, 8, 27, and 216.

Actual case study: comparison of xylene with mercury showed xylene bulb volume one-fourth mercury bulb volume for a given range and for actual instruments on the market, a xylene spring direct-connected, and a mercury spring plus a mechanical movement for obtaining equal angular travel by multiplying spring deflection.

(7)—Slight: Even with smallest standard bulb, effect of change from ice to steam on 10 ft. capillary is claimed to produce 1°F. error in indicating bulb temperature. Some makers supply "full compensation" systems (see third method in Note 3).

(8)—Compensating device is within area formed by outside diameter and height of spring.

(9)—Lowest working pressure, at low end of usual ranges, is 300 lbs./in.^{2}; 10 ft. head of xylene = 3.5 lbs./in.^{2}.

(10)—Characteristics of many volatile liquids being known, makers can supply proper filling for each range specified. It always is advisable to specify not only the range but the *zone* within the range where accuracy is most needed. Reason: sensitivity increases with the temperature.

(11)—A "progressive" scale is one which is "closed" at its lower end and "open" at its upper end. Such scales are made necessary by the non-linearity of vapor pressure with temperature, unless by the use of a suitably shaped cam or other movement the uncoiling of the spring can be made to produce a uniform motion of the pointer for every degree throughout the range.

(12)—The capllary and spring for the usual ranges are completely filled with unvaporized liquid, with vapor generated only within the bulb. If bulb is excessively small or if tube is excessivey long, cold ambient temperature (reducing volume of liquid in tube and spring) would leave insufficient liquid in bulb where there must always be a free surface.

(13)—In the usual arrangement, when any portion of the tube or spring is subjected to a higher temperature than that of the bulb, accuracy is destroyed, for the spring reacts to the pressure of the higher temperature as long as there is any liquid exposed to the hot spot. Capillary bore diam. being about 1/50 of bulb I.D., liquid is quickly driven toward bulb. After initial "kick," in some cases, there may be no permanent error.

(14)—Considerably when working pressure is low. 10 ft. water head = 4.33 lbs./in.^{2}. Assuming a high Baumé hydrocarbon, we get about 3.5 lbs./in.^{2} for every 10 ft. Even more important is total impairment of accuracy when, bulb level being higher than spring and no liquid being left in a small bulb, absence of a liquid surface in bulb makes pointer or pen-arm stay where it is until some liquid gets back into bulb. At the higher pressures (upper parts of ranges) the hydrostatic effect becomes negligible; and the use of a transmission liquid sealed off from the active liquid by a bellows permits installing the bulb at a higher level than the spring.

(15)—Range characteristics depend on liquid used. Liquids are chosen which will produce a vapor pressure sufficient to assure fair sensitivity at the lower end of the specified range. The upper end naturally depends on the critical temperature and critical pressure.

(16)—Fluid friction in the capillary is negligible, the medium being a gas, and the length limitation is imposed by the temperature errors. In plants provided with room temperature control, longer tube lengths may be used. Some makers supply "full compensation" systems: see third method in Note 3.

(17)—The largest practicable volume of gas should be contained within the bulb and therefore the longest length which the applications can take should be specified, even where maker can supply "full compensation."

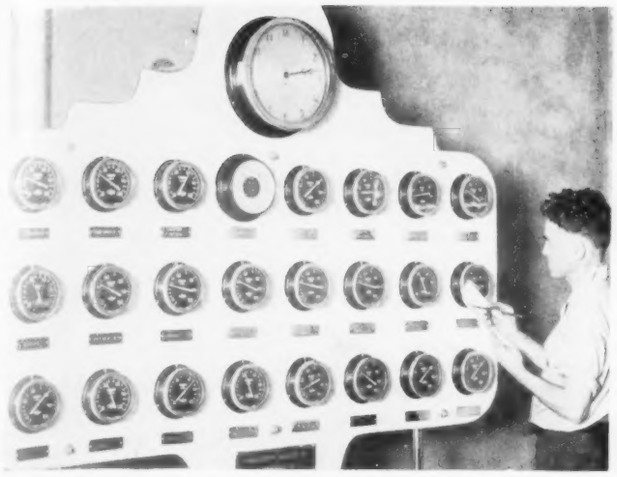

Fig. 1. Centralization is made possible by the use of pressure-spring thermometers. *(The Foxboro Co.)*

permit greater distances but in many plants 100 feet is ample. The capillaries of pressure-spring thermometers must not be cut, whereas no permanent injury is done by breaking an electrical conductor. The entire tube-systems of pressure-spring recorders and controllers of some makes are removable, thereby lessening the "convenience handicap" in comparisons with electrical instruments.

While the maximum length of the connecting tube is limited by the filling of the system and by the method of compensation for tube errors, there is no minimum length. Hence the popular "stem" forms of pressure-spring thermometers (some of which are illustrated herewith) and the "room temperature" or "self-contained" forms of recorders. Short-stem dial thermometers have in recent years been sold in large numbers for use on ice-cream freezers, on Diesel engines and on other classes of industrial equipment where for various reasons they have won preference over industrial mercury-in-glass thermometers. Of the pressure-spring dial thermometers in use, however, it is estimated that about 50% are of the remote-reading form. Of the recorders, at least 90% are of the distance form.

In addition to the information about scales in Table III, mention may be made of the possibility of *special scales*, including the important kind produced by the *retard movements*. These scales are extremely valuable in connection with processes where the "one best" temperature has been determined and is not subject to change. For example, the pasteurization of milk. An "open" scale is required around the *pasteurizing* temperature of 143°, 144° or 145°F. Some states require a full 1/16″ for each degree. The bulbs are subjected to the temperature of boiling water when the equipment is *sterilized*, so that the upper end of the scale must be, say, 220°F. Milk *cooling* temperatures must also be measured and this requires a lower limit at, say, 30°F. The total scale range therefore must be 190 degrees. Multiplying 1/16″ by 190 would give nearly 12″ scale length, but various mechanical movements, practicable with pressure-spring thermometers, provide "milk scales" only 4″ long, yet complying with the law.

2. Implications of "Pressure-spring"

In considering the characteristics of the four classes and their relative suitability for various applications, it frequently is useful to think of the instrument proper as an ordinary Bourdon gage and to take into account its pressure range. An extreme example may be cited to emphasize this pressure-measurement factor: Imagine a Bourdon gage graduated 0-30 lbs./in.^{2} abs., and calibrated for sea-level atmospheric pressure. At sea level it will indicate the true absolute pressure of any sealed container to which it is connected; but if used in an airplane, its readings would have to be corrected for barometric error. In fact, a gage of such low range could be used as an altimeter. But if a Bourdon gage graduated 0-750 lbs./in.^{2} is used on an airplane, the

Fig. 2 (right). Mercury, 8″ size, sanitary tube, connection for inserting through side of vat. *(Taylor)*

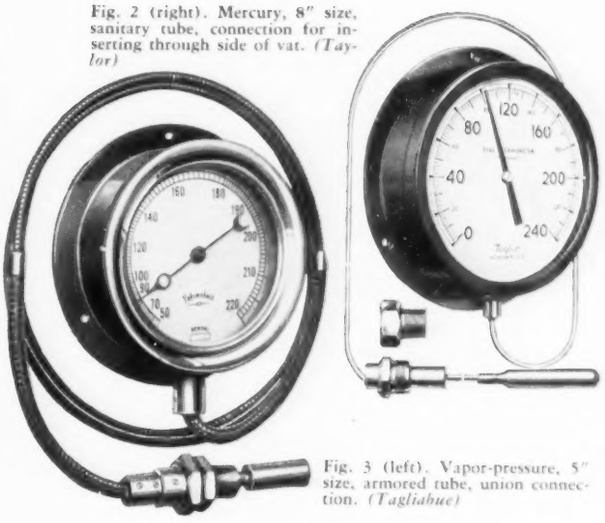

Fig. 3 (left). Vapor-pressure, 5″ size, armored tube, union connection. *(Tagliabue)*

Fig. 4 (below). Duplex for "in" and "out" temperatures. 8″ size. *(Foxboro.)*

Fig. 6 (below). Quadrant form with back stem. *(U. S. Gauge Co.)*

Fig. 5 (center). Quadrant form, xylene-filled, straight stem. *(Moto Meter Gauge Div., Electric Auto Lite Co.)*

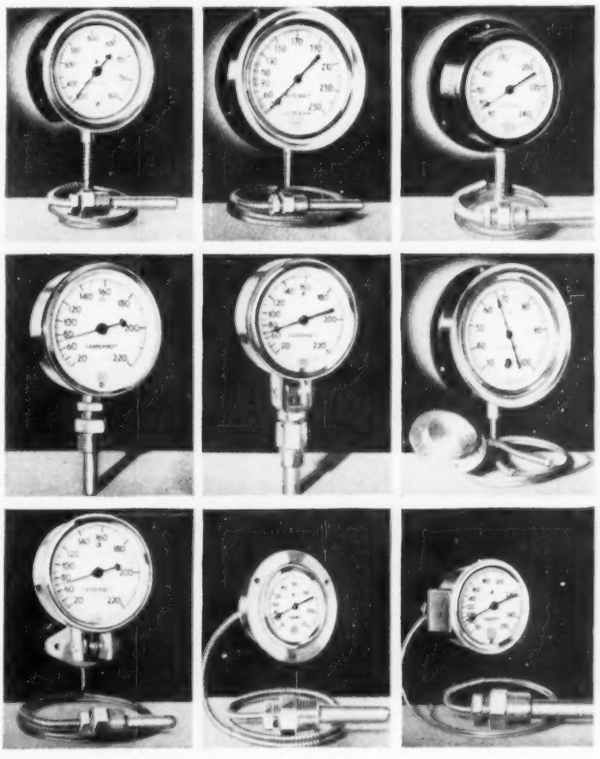

Fig. 7. Nine different styles of the round form. *(U. S. Gauge Co.)*

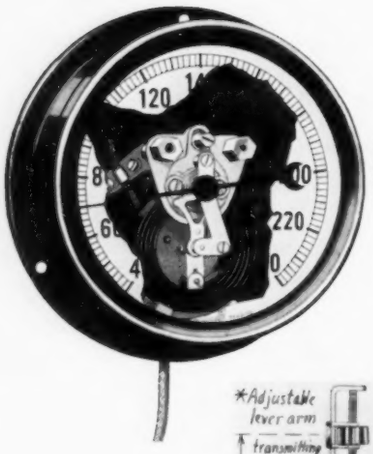

Fig. 8. Mercury system, spiral spring, dial form, geared movement. *(Consolidated Ashcroft-Hancock Co.)*

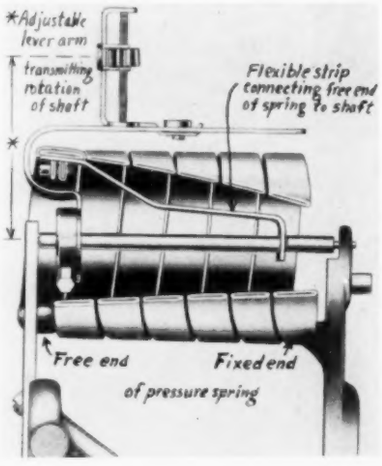

Fig. 9. Close-up of helical pressure-spring and of one manufacturer's method of fixing one end of the spring and accomplishing other results. *(The Foxboro Co.)*

barometric difference between sea-level and customary ceiling will produce an error of less than 1% of its scale range.

Another extreme example: Imagine a mercury-filled system consisting of bulb, 30″ tube and pressure-spring, the spring being borrowed from the 0-30 lb. gage referred to in the preceding paragraph. In round numbers, the mercury-column equivalent for pressure is two inches of mercury per pound, or 30″ mercury for the 15-lb. sea-level atmosphere. Therefore when the bulb of this system is at the same elevation as the spring, the gage reads 15; when the bulb is 30″ lower than the spring the gage reads zero; when the bulb is 30″ higher than the spring the gage reads 30. Substitute the high-pressure spring (0-750 lbs. or 50 atmospheres) and the 60″ difference between "bulb higher" and "bulb lower," which corresponds to two atmospheres, will move the pointer over only 4% of the scale range.

Still another extreme example: The same mercury system, but with a gage having a scale range of 100 to 130 lbs./in.^{2} (or 200-230, or 1000-1030 . . .). If the calibration pressure within the system is such that the gage reads zero with the bulb at the same level as the spring, the pointer will travel half-way across the scale when the bulb is raised 30″.

Conclusion: the external and internal pressure errors are in inverse ratio to the "power" or stiffness of the springs. With sufficiently "powerful" springs, designed for *sufficiently long pressure ranges*, these errors may be made negligible.

This is tantamount to saying that a pressure-spring thermometer is a heat engine—which would not be a far-fetched analogy, for an important characteristic of any system is the ability to do the work of driving a pointer or pen-arm over the requisite distance with sufficient force to minimize the resistance of friction of pen on chart, the other friction factors and the other sources of error. Force times distance, that is to say, work, or *energy*. The comparison on the basis of energy is frequently used in the detailed analysis of different classes and types of pressure-measuring instruments, some aeronautical instrument engineers and geophysical experts having carried it out to a high degree of mathematical refinement. With regard to pressure-spring thermometers for industrial service the energy question is frequently summarized by the assertion that the spring is "powerful enough" or "stiff enough." A more exact summarization is to state the obvious rule that—

other things equal, the tube-system producing the greatest pressure increment per unit increment of temperature is the most energetic,

from which rule certain deductions and rough mental calculations can be made with the greatest of ease when comparative figures (on the various coefficients involved, etc.) are obtained. An example will be found several paragraphs below. Before coming to it, however, it is useful to set forth certain inherent operating characteristics of the four classes.

3. Operating Characteristics of the Four Classes

I—ASSUMING A NEGLIGIBLY SHORT CAPILLARY

Mercury. The mercury-in-steel system resembles the ordinary mercury-in-glass thermometer in that the greater part of the mercury must be contained in the bulb and the smaller part inside the pressure spring. The utilized thermal property of mercury is expansivity. Mercury has the lowest expansion coefficient of the liquids commonly used in pressure-spring thermometers: approximately one-seventh that of xylene, for example. Therefore, considering only this ex-

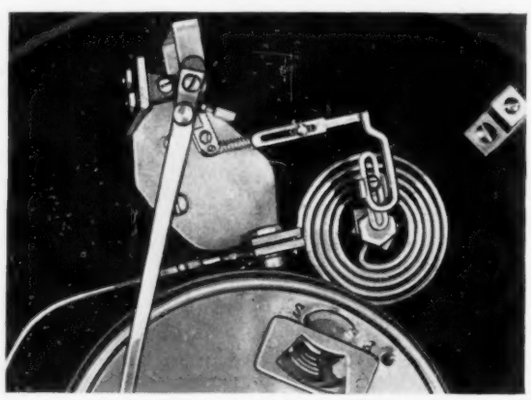

Fig. 10. Spiral steel spring of a mercury system recording thermometer. *(C. J. Tagliabue Mfg. Co.)*

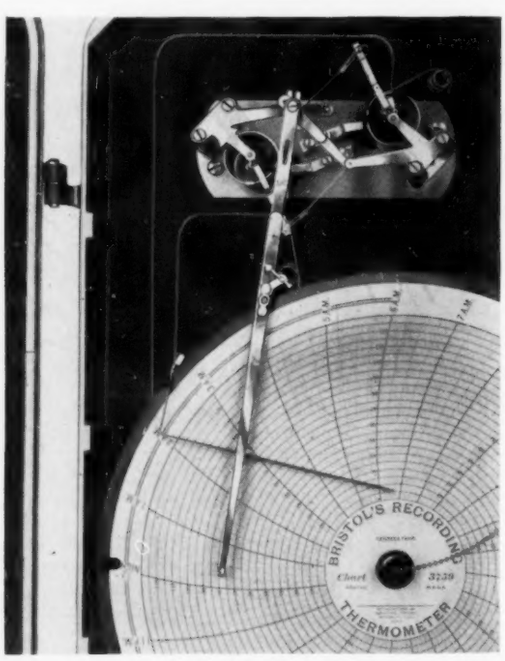

Fig. 11. Two springs are seen in this recorder: one is for ambient-temperature compensation. *(The Bristol Co.)*

pansion coefficient, the bulb length of a mercury system should be seven times the bulb length of a xylene system (having the same bulb diameter, the same range and the same internal volume of pressure spring) in order to produce the same uncoiling of the same spring for the same temperature rise at the bulb. However, this small expansion coefficient of mercury permits obtaining the same angular deflection from a much smaller spring—which is an advantage. Moreover, the extremely small compressibility of mercury, and the wealth of accumulated knowledge of steel metallurgy, make possible *in actual practice* the manufacture and standardization of steel pressure springs of relatively small internal volume for relatively long total lengths of flattened tubing. The specific gravity of mercury is around 15 times that of most thermometric hydrocarbons. The two kinds of altitude errors would therefore be serious (as was explained above) if it were not for the possibility of using springs of adequately long pressure ranges. The scales are of mercury systems uniform, but it must be borne in mind that over a long range (say 200°C. or more) mercury expansion departs appreciably from the thermodynamic temperature scale law.

Xylene. In a xylene system the same principle of operation is used, but the properties of hydrocarbon liquids together with practical requirements of design and construction compel the use of relatively weaker springs. Uniform scales are provided; in general the deviation of the expansion coefficient from the thermodynamic scale law is negligible.

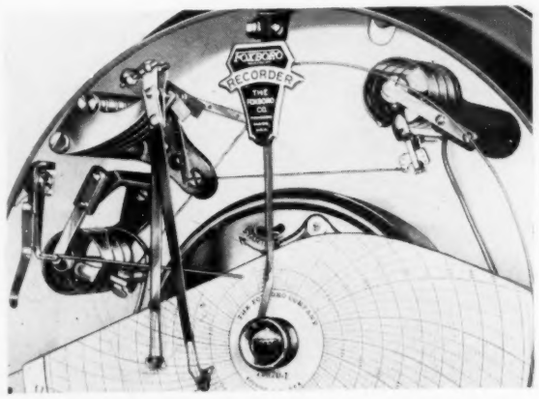

Fig. 12. Mechanism of a two-pen pressure-spring recording thermometer. *(The Foxboro Co.)*

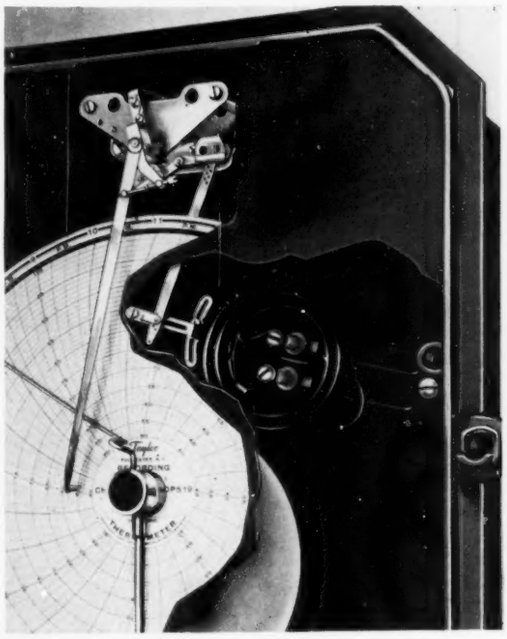

Fig. 13. Mercury system, spiral spring. Provisions for adjustments plainly shown in this figure. *(Taylor Instrument Companies.)*

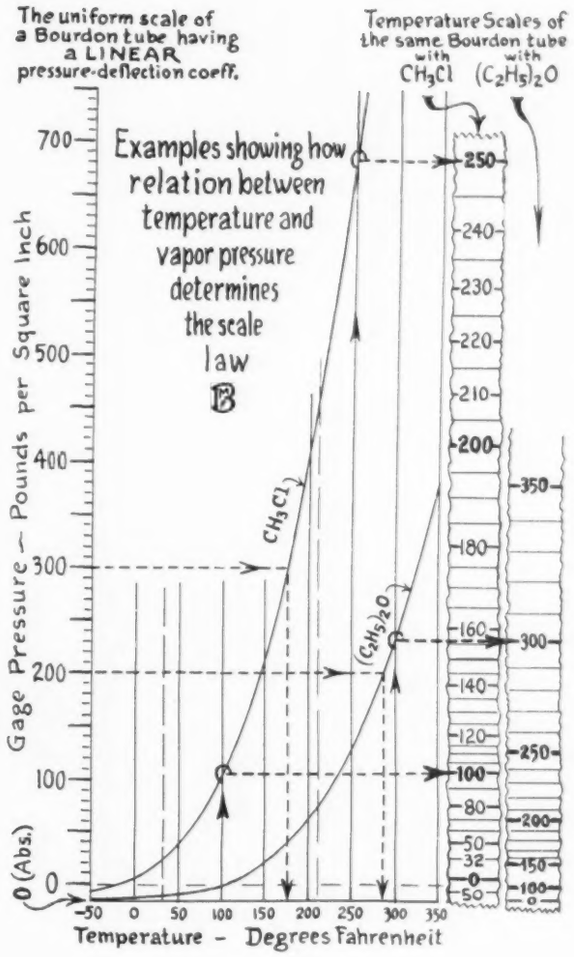

Fig. 14.

Vapor-pressure. A vapor pressure system makes use of the fact that the pressure in a vessel containing only a liquid and its vapor increases with the temperature and is independent of the volume so long as liquid remains. In this class of thermometer, therefore, the "strength" of the pressure-spring must be suited to the liquid and to the temperature range. The scale is "progressive"—which is desirable where one zone is of particular interest and where such zone can be the upper portion of the scale. Study Fig. 14, which has been drawn in preference to a thousand words of text. It may be added, however, that the 0-350°F. scale (shown at the right) can be made as long *in inches* as the 0-250 scale, even if the same pressure-spring is to be used. This is done by adjusting the link ratios, etc. Note that the spring (a stiff "thousand-pounder") will then be worked far below its elastic limit. On the other hand, when a low-pressure spring is used to suit the curve of a low-boiling-point (low-range) liquid, excessive pressure caused by exposure (of any part of the system) to excessive temperature would be injurious. This is true of all systems but the danger is greater with vapor-pressure systems as the shape of the typical curves shows. To prevent over-ranging, the Mason-Neilson Co. employs an auxiliary bellows, "normally retained at a constant volume, but which is permitted to expand should the system pressure become excessive."

Gas. The gas-filled systems utilize the simple relation which, for an ideal gas, is:

$$\text{Abs. Temperature} = \frac{\text{Pressure} \times \text{Volume}}{\text{a constant}}$$

and which is the basis of the constant-volume hydrogen

thermometer formerly used for high-precision work.* But the volume of a gas-filled system varies with the spring deflection. Moreover, hydrogen and helium (the "nearly perfect" gases) transpire through the pores of most bulb metals, especially at temperatures above the vapor-pressure thermometer range limit, compelling the use of "heavy" gases which deviate appreciably from the gas laws (though less than do liquid-expansion coefficients from linearity). The total deviation, in practice, is small enough for the instrument scales to be uniformly graduated. With regard to energy—to the work of driving the pointer or pen-arm —the gas laws provide two interdependent solutions of the problem, namely: make the bulb volume or the initial pressure, or both, as high as possible. The user can specify as large a bulb as the apparatus or pipe can take; the manufacturer provides the highest practicable *initial* pressure (pressure at the lower end of the scale range). The gas laws set practical limits to these interdependent solutions of the problem. Thus, in a system of the customary dimensions listed in catalogs, it obviously is impracticable to obtain adequate energy for complete travel across the scale from a 5° rise in temperature. That is one reason why gas-filled pressure-spring instruments are made up for relatively long temperature ranges: the longer the range, the stiffer the spring that can be used.

Maximum Possible Pressure Increment per Unit Increment of Temperature at Bulb. This can be roughly calculated from the expansion coefficients of the liquid and of the bulb material, and the compressibility of the liquid, without need of putting into the equations the actual volumes involved, since these cancel out. The assumption is made that the bulb is subjected to a 1° (C. or F. depending on the system of units) rise in temperature, and that the volume of liquid thereby displaced into the capillary is driven back into the bulb by the application of an external force to the pressure spring which causes it to "recoil" exactly as much as it had "uncoiled." This gives the unit pressure increment and hence the energy factor for full deflection corresponding to total scale travel. This treatment is by no means rigorous, but the percent error in the final results remains practically constant in a series of computations, so that for *comparative* purposes this rough method will serve. For example, starting from the following data

Ratio of compressibility of mercury to organic liquid 3.7 to 145
Ratio of expansion coef. of mercury to organic liquid 18 to 163
Bulb material for each: steel (exp. coef. in same units, 35.7)

we obtain 600 lbs./in.^{2} for mercury and 150 lbs./in.^{2} for the organic liquid considered in this example.

Thermometric Lag. A compromise must be made in practice between the requirement of a long pressure range for a conveniently short temperature range, and the wall thickness of the bulb. The greater the bulb-wall thickness, the greater the lag. This lag may be relatively unimportant in the case of indicators and recorders, but it becomes important when the bulb is the primary element of an automatic control system.

Since vapor-pressure systems must be designed with spring characteristics suited to the relation of temperature to vapor pressure of the filling, these systems are simply not used on applications requiring springs as stiff as those possible with mercury systems. In such applications, therefore, thin-walled bulbs may be used. Thus the general statement can be made that the vapor-pressure class systems respond more quickly than do the others. It must be emphasized that the reason does not lie in the inherent superiority of the vapor pressure curve as a thermometeric property of a substance.

The gas-filled systems, as actually manufactured, and considering the various design factors, are the slowest.

The mercury systems, as manufactured, are faster than the xylene systems as manufactured.

*The Normal Hydrogen Thermometer was used as an official standard until 1927, since when the National Bureau of Standards and similar institutions have been using resistance thermometers, thermoelectric pyrometers and optical pyrometers. See Chapter I, "The International Temperature Scale."

Differential Pressure Effects. In the use of mercury-in-glass thermometers, experience shows that the fluctuations in ordinary barometric pressure become a source of error as the bulb walls are made thinner (to minimize lag) and as the bulb volume is made larger (to shorten the range). The reason is that for each temperature there is a definite equilibrium pressure of the gas above the mercury thread. A precision mercurial thermometer may show an error of 5% of its scale range when used on an airplane flying at the altitude prescribed for airliners. In the use of pressure-spring thermometers, the analogous source of error is the differential pressure between that surrounding

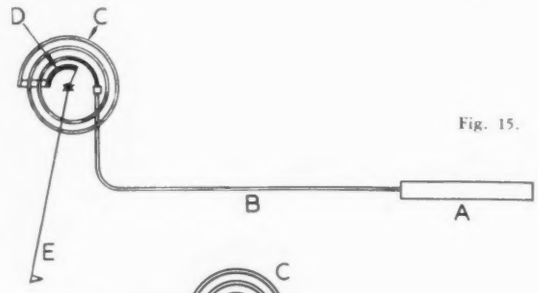

Fig. 15.

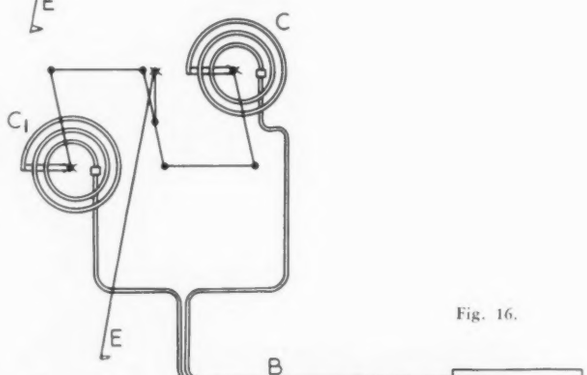

Fig. 16.

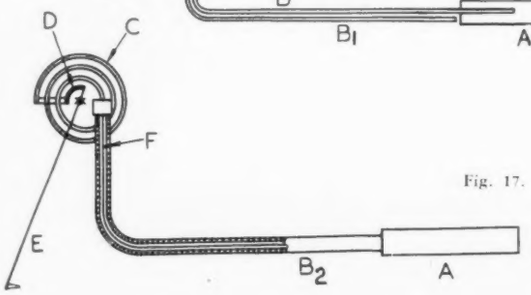

Fig. 17.

A – BULB
B – CAPILLARY TUBE
B_1 – COMPENSATING TUBE
B_2 – ANNULAR-CAPILLARY TUBE (SELF-COMPENSATING)
C – MEASURING ELEMENT
C_1 – COMPENSATING ELEMENT
D – COMPENSATOR
E – POINTER
F – INVAR WIRE

the bulb and that surrounding the rest of the system. This effect may be ascertained by simply screwing the bulb into a section of pipe or other suitable vessel connected with a gage tester or with any source of controlled pressure. It is negligible, as a rule, when the bulb is of rugged construction. The use of separable sockets, likewise, "damps" the variations of pressure which can affect the bulb.

Compensation for temperature fluctuations at the location of the instrument—the "head" of the system, containing the pressure-springs—is known as *head compensation* and is embodied in the mercury, xylene and gas-filled pressure-spring thermometers, its usual form being a bimetallic element between the spring and pointer or pen-arm. In the vapor-pressure instruments it is only required in exceptional cases.

II—LONG CAPILLARIES

The foregoing discussion of charactistics has purposely considered the systems as consisting of bulb and spring connected by a capillary too short to be of consequence.

The increasing size of processing units such as fractionating towers, etc., as well as the increasing tendency toward centralized control boards in all industries and in public buildings, have not only made the "tube error" a factor of importance but have led to the embodiment of various ingenious schemes of "partial compensation" and "full compensation." The relative merits of various makes cannot be discussed here. Nor can even a small number of patented systems be shown in diagrams and their features discussed. However, under the auspices of the Committee on Instruments and Regulators of the Process Industries Division of the ASME, there was presented in 1938 a paper* containing a discussion of various general types of compensating schemes, and this paper appeared in the *Transactions of the ASME*. From this publication of a national engineering society, therefore, it is appropriate to reproduce some of the schematic diagrams. Figs. 15 to 20 inclusive are from this source, but the present writer has made some slight alterations, which he believes will be found acceptable to everyone concerned.

Figs. 15, 16 and 17 apply equally to the mercury, xylene and gas systems; Figs. 18, 19 and 20 apply only to the vapor-pressure systems.

In Fig. 15 there is shown the usual short-tube mercury, xylene or gas system, with a device *D* which compensates for the effects of temperature on the volume of liquid or gas in the spring.

Fig. 16 illustrates a method of full compensation employing a second pressure spring, the capillary tube of which runs the full length of the main capillary tube, stopping short at the bulb. The proportions, pressures, linkage design, etc., are such that a given change in temperature along the main capillary, producing a certain deflection of the measuring element, produces also an equal and opposite effect on the pointer or pen-arm. The second "capillary" need not itself be a second *tube* enclosed in the outer protecting armor or flexible tubing: it may be the annular space between the transmission capillary tube and an outer tube.

Fig. 17 is a simplified diagram of a system brought out in 1921 by one company, but made in slightly different forms by different companies. The tube is made of an alloy (a ferrous alloy for mercury) of relatively high expansion coefficient; the wire is made of one of the invar type alloys; the annular space between tube and wire is a capillary connection between bulb and pressure spring. This annular volume, therefore, has a *differential* coefficient of expansion which is designed to equal the expansion coefficient of the mercury, organic liquid or gas, allowance being made for pressure effects.

In the vapor-pressure systems, the tube errors are radically different—ambient temperature fluctuations causing temporary errors, as explained in the notes accompanying

*L. G. Bean, Sales Manager, The Bristol Co. "Pressure Type Thermometer Systems." *Trans. ASME*, Vol. 60, No. 8, Nov. 1938, pages 657-663. Abstract: *Instruments*, Vol. 12, Nov. 1939, pages 298-300.

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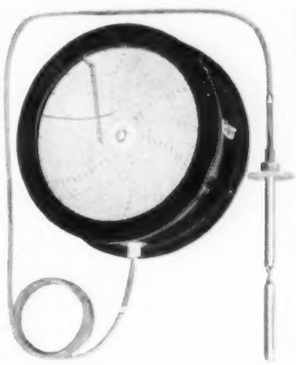

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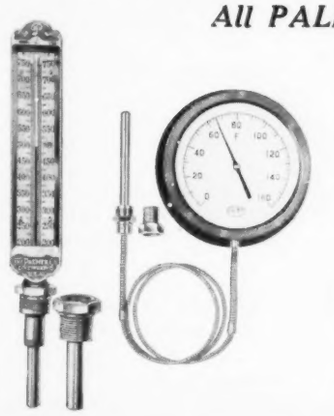

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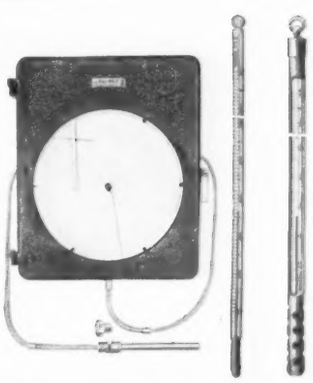

Table III. The principal source of error is generally caused by the absence of a liquid surface in the bulb, and this may occur not only by reason of long capillaries but even from failure to follow directions pertaining to position of bulb.

Fig. 18 shows the customary arrangement, in which the chief design precaution is simply to have the capillary extend into the liquid.

Fig. 19 represents what the author of the ASME paper designates as the "adjusted" type. The principal difference is the provision of a larger bulb.

Fig. 20 shows a design in which a transmission liquid is used, sealed off from the thermometric liquid selected for its vapor pressure curve. The sealing is effected by a flexible member, a *bellows* form being shown in the drawing. This permits the use of long capillaries because temperature fluctuations along the capillary or at the head of the system do not appreciably alter the characteristics. (The vapor-pressure principle, of course, is that the pressure of a vapor in contact with its liquid is independent of the volume.) The only possible source of error introduced by a sealing member arises from the fact that such a sealing member cannot be ideally slack. (We are not considering accidents such as leaks.)

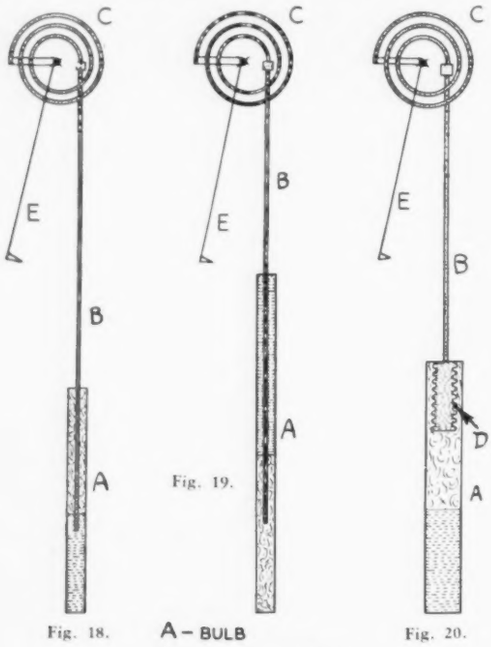

Fig. 18. Fig. 19. Fig. 20.

A – BULB
B – CAPILLARY TUBE
C – MEASURING ELEMENT
D – DIAPHRAGM BULB
E – POINTER

Long capillaries may give rise to errors, at low regions of ranges, when the bulb and spring are at variably different elevations: the pressure at the spring is the algebraic sum of *vapor*-pressure in bulb ± hydrostatic effect of *liquid*. Study Fig. 14.

4. Miscellaneous Notes

The motive power of the system may be made to actuate the pointer, pen-arm, or other element, either *directly* or by means of intermediate *mechanical movements*. The direct indication method would seem to possess the advantage of simplicity, and other mechanical advantages, but impressive arguments in favor of various movements make manufacturers' sales literature interesting as well as instructive reading.

Springs. There is no such thing as a perfect spring—spiral, helical, volute, Bourdon, diaphragm, bellows, capsular, etc. Nevertheless, instrument designers and metallurgists, after working together for years, have developed quantity-production springs that show excellent pressure-deflection graphs—with hysteresis loops no thicker than a soft pencil line on a letter-size sheet of coördinate paper. Thermometer springs are subjected to such severe service that they lose their initial characteristics in the course of time. (A watch hair spring may oscillate millions of times and still help the watch keep good time, but this is not a fair comparison. In the first place, the variations in the elasticity of a hair-spring are largely compensated by the isochronous dead-beat escapement and balance wheel. In the second place the area stresses in thermometer springs are much greater fractions of the elastic limit.) Sensitivity depends on the amount of *spring deflection energy* per unit change in temperature. If multiplication (mechanical movements) or magnification (long pointers) are carried too far, they impair *accuracy* by accentuating both hysteresis and non-linearity.

All springs "fatigue;" some materials are better than others.

"Complicated" vs. "simple" movements. When non-linearity sets in, there is nothing to be done about it in a direct-connected spring-and-pointer instrument; but in its effects may be minimized (or sometimes fully corrected) by a system of adjustments, necessarily comprising a plurality of screws, levers, bearings, and other such elements which, of course, *may* wear, collect dust, etc. It is not a "choice of two evils," for the errors—both of fatigue and of wear—are seldom of consequence in industrial work. The choice of any construction should rest on the intended use of the instrument: If for a small part of the range, the simplest forms may do, because any thermometer may be adjusted for accuracy at *one* point. If permanent accuracy to within 1% is desired throughout the range, the wisest investment may turn out to be an instrument of higher first cost and which requires careful attention every few months or so.

Fig. 21. Principal Forms of Bulbs, Connections and Sockets for Industrial Pressure-Spring Thermometers *(Taylor Instrument Companies)*.

Illustrations show products of one manufacturer but following discussion applies to various makes.

A—Plain bulb, adjustable clamp flange by means of which bulb may be positioned any distance from wall or cover through which tube is passed. Suitable for air and gas temperatures when circulation is adequate, but mostly used for tanks—being inserted from top. The flange may be replaced by an adjustable ("split") union connection hub for insertion through the top of such equipment as pasteurizers, etc., where sides and bottom are steam-jacketed. The bendable extension bulb is similar in appearance but the distance from connection to bulb is not adjustable and the connection is pressure-tight.

B—Long capillary bulb, sometimes known as super-sensitive, sometimes formed as a helix with a stiffening rod at the axis, for air or gas temperatures. When vapor pressure, "hottest spot" temperature affects pressure-spring; liquid expansion or gas filled bulb "averages" temperature.

C—Union connection—most popular fitting—permitting easy installation.

D—Same, but with extension neck between pipe thread and wrench-head for use on lagged equipment.

E—Separable socket connection. Remains pressure-tight when bulb is withdrawn and protects bulb from corrosion, etc.

Inaccuracies resulting from careless specifications when ordering give the greatest trouble in service. Table III and the notes should obviate this. Just one example: In specifying a gas-filled pressure-spring thermometer get the largest available and convenient bulb volume, and specify the minimum usable tube length regardless of hazy possibility of future use on another application calling for a longer tube. If for a walled or jacketed application don't save a few dollars and get a bulb so short that it will measure the temperature of the wall and not of the flue gases or whatever there is within the enclosure.

The possible effects of accidental breakage may be of interest to the process man. A gas-filled system can be

smashed by a clumsy workman without the escaping gas harming machinery or equipment or contaminating edible products, chemical mixtures, etc., since nitrogen is commonly used. The same cannot be said of other fillings.

Table III gives the *material* with special reference to the *bulbs*. While any bulb may be protected by a *separable socket* of any metal or alloy, and while it may be lead-covered, or tinned, or plated with chromium or other metals, the *capillary must not be forgotten*. The capillary may be protected by any one of a great variety of tubings or armors—spiral, woven, lead, etc. The exposure of the tube to destructive influence is sometimes overlooked in specifying the instrument, resulting in rapid deterioration of instruments that should give many years of satisfactory service. The strength of the tubing—whether single or combined—is another consideration. Mention may be made of the unique phosphor-bronze capillary tubing, standard with one manufacturer, which is originally round in cross section, then squeezed to a square, then the sides of the square are squeezed in, resulting in a "four-pointed star" cross section, producing a small bore area and increasing flexibility without (it is claimed) decreasing strength.

Bulbs, Sockets, and Connections—All of the ingenious styles described above under "Industrial Thermometers" are available with pressure-spring thermometers, except such styles as "bare-bulb" and others peculiar to industrial glass thermometry. In addition, there are "long capillary" bulbs applicable to rooms, ovens drying compartments, etc., and other styles possible only with distance thermometers. Among these latter may be mentioned the "bendable extension" allowing the bulb to be out of line with the axis of the pipe-thread connection, the elbow connections (plain or with lead-covered funnel for corrosive exposure) and special bulbs, sockets, and connections for various specific industrial applications.

CHAPTER VII
RESISTANCE THERMOMETERS

1. Characteristics

This last group in the thermometer division of industrial instrumentation possesses one important advantage over the other groups: the primary element may be disconnected from the indicator, recorder or controller.

Therefore a number of resistors ("bulbs") placed in widely separated locations may be successively connected to one electrical measuring instrument. This centralization is of importance in industrial work where comparisons of temperatures are desirable at a moment's notice. In cold storage work, thirty or more bulbs are not uncommon for a single indicating instrument.

It also is possible to obtain instruments so calibrated that direct readings can be taken showing either (a) the *average* temperature of two or more points, or (b) the *difference* in temperature between two points.

The lowest temperature accurately measurable with industrial forms of resistance thermometers is about —165° C. (—330° F.); the highest about 1000° C. (1800° F.).

While pure platinum continues to be the standard for precision work, resistance elements with pure nickel or pure copper coils are much more widely used in industry today. There has even appeared a liquid resistor—an electrolyte in thin glass tubing—claimed to possess distinctive advantages.

The intrinsic accuracy of the resistance thermometer is so high that under laboratory conditions the resistance thermometer is used as the International Standard between -190°C. and 660°C., but a resistance thermometer is more "complicated" than a mercurial or pressure-spring thermometer and therefore industrial service may cause large errors through poor contacts, rough handling, deterioration or contamination of the platinum, copper or nickel, defective insulation and other causes difficult to prevent altogether in plant service. In good hands and when the precautions recommended by the manufacturers are taken, the accuracy will be better than that of any other grou pof industrial temperature instruments. It is stated by one manufacturer that "at 32°F. the accuracy is ±1/10°F." This is an ordi-

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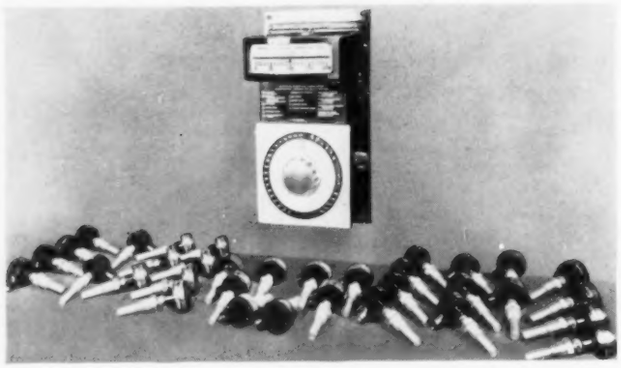


Fig. 1. Outstanding characteristic of electrical thermometry is that one instrument can serve many points. *(Thwing-Albert Instrument Co.)*

nary industrial instrument. There are commercially-available precision calorimetric and other special-purpose resistance thermometers.

In a plant or department where no electrical temperature instruments have ever been used, the acquisition of the first resistance thermometer may meet with "sales resistance" if for no other reason than the fact that a complete resistance thermometer set may include a number of "electrical gadgets," in addition to the electrical instrument itself. To engineers unfamiliar with resistance thermometry the mere thought of looking after an apparently complex outfit is a deterrent. In reality, no engineer need hesitate. Besides, there are resistance thermometers on the market which require no high-grade constant-voltage batteries (or no batteries at all), and in which no lead adjustments are needed after an initial check. Furthermore, doesn't a good radio work well in spite of its complexity?

Where accurate temperature measurement is necessary, as in steam work, calorimetry, determination of optimum process temperatures, etc., many engineers are in the habit of resorting to the etched-stem laboratory thermometer immersed in a mercury well, sometimes forgetting that the mercury-in-glass method of thermometry is subject to errors and requires corrections when extreme precision is required, whereas resistance thermometry would seem to be preferable, as will be seen by the following comparison:

1. *Stem Exposure*—The reading of a resistance thermometer with compensated leads depends only on the temperature of the coil and not on the temperature of the stem, provided that the immersion is sufficient to avoid errors due to conduction or convection along the stem.

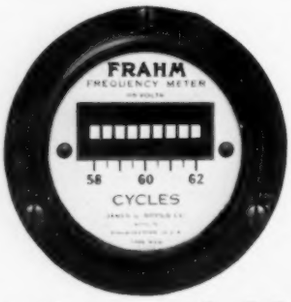
2. *Aging effects* of mercurial thermometers arise chiefly from the small expansibility of mercury combined with the relative instability of the glass tube. In resistance thermometry, the tube of quartz or other material, which contains the coil, has nothing to do with the reading, and the effect of any possible strain of the fine wire of the coil is minimized by its small dimensions and by the large temperature coefficient of resistivity, which is more than twenty times greater than the coefficient of apparent expansion of mercury in glass. It is not surprising, therefore, that zero creep of a resistance thermometer should be practically negligible, provided that the wire is not strained or contaminated. With ordinary care, changes of zero due to exposure are *less than the limit of accuracy of observation*

3. *Pressure Correction*—The effect of change of pressure on a resistance element of the ordinary tube form is nil or negligible. Even if the wire is naked and directly exposed to large changes of pressure, the effect is extremely small and it is known.

4. The only source of error "analogous" to the irremediable effects of capillarity which are troublesome with delicate mercurial thermometers, is friction in the galvanometer or other electrical instrument, but this is seldom troublesome and generally remediable.

2. Primary Elements or "Bulbs"

The operation of a resistance thermometer depends upon the variation with temperature of the resistance of an electrial conductor. The primary element, responding to tem-



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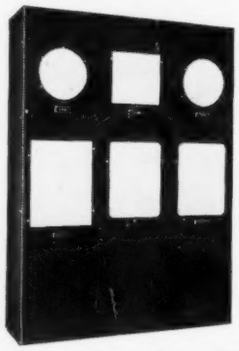

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perature, is generally a resistance coil or spiral. This coil, together with its frame, tube and other necessary accessories, is itself called "the thermometer" in some publications, but in industrial work the entire primary element may simply be called the "bulb."*

For industrial service, the resistance coils are made of platinum, of nickel or of copper. In a common form of 8-ohm platinum coil, fine wire is wound upon a frame made of crossed strips of thin mica notched at the edges to hold the wire in place. From the ends of this coil, lead wires of platinum or gold are carried to the "terminal head" where

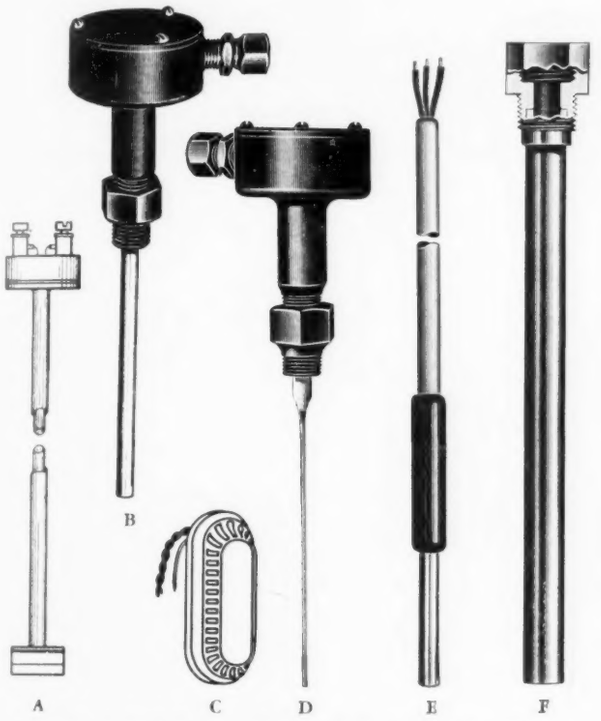
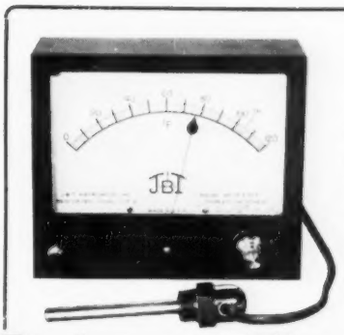


Fig. 2. Typical Industrial Forms of Resistance Bulbs, etc.
A—Contact Plate "Bulb" for Bearings, Insulation, Hot Plates, etc. *(Chas. Engelhard, Inc.)*
B—Protected Nickel Coil Bulb. *(Leeds & Northrup Co.)*
C—Wall Type Sensitive Bulb for Temperature. *(Foxboro Co.)*
D—Flattened Protecting Tube Bulb. *(Leeds & Northrup Co.)*
E—Nickel Coil Bulb with Rubber-Covered Leads. *(Leeds & Northrup Co.)*
F—Separable Well or Socket *(Leeds & Northrup Co.)*

the binding posts are fixed. The lead wires are insulated and held apart by mica disks through which the wires are threaded, and which serve to minimize convection. The coil is protected by a porcelain or quartz tube which fits into the terminal head. For industrial use the refractory tube itself may be enclosed in a strong sheath or well as in the case of "industrial" and pressure-spring thermometer bulbs which are enclosed in bulb chambers and separble sockets. In another form, a 50-ohm coil of fine platinum wire is wound upon a fused quartz rod and fused inside a quartz tube, so that the platinum is entirely embedded in quartz. Gold leads are carried from the coil to the terminal head. The fused quartz insures high electrical insulation, while still preserving excellent heat conduction. This form of bulb is compact, and the platinum is thoroughly protected against deterioration. Transparent fused quartz is unattacked by most acids and may be subjected to violent temperature changes without cracking.

The variety of primary elements for industrial applications is so great that space limitations prevent a classified list. Suitable bulbs are available for indoor or outdoor atmospheric temperature, refrigeration work, steam work, electric transformers, ovens, dryers, bearings, oil baths and

*A specific term is obviously needed. In thermoelectric pyrometry there has been a movement to call the essential elements of thermocouples "thermels." Recently, the Leeds & Northrup Co. has been designating its resistance-thermometric primary elements "Thermohms"—a name which this writer likes.



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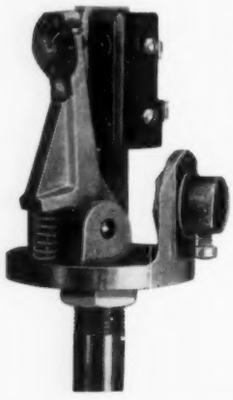

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other metallurgical applications, etc. Copper-nickel tubes, round or flattened, are available for feed water heaters or lines. Separable sockets, in which a number of bulbs are interchangeable and which themselves have standard thread or flange connections, are used against corrosive conditions, against pressure up to 1500 lbs./in.^{2} or higher.

3. Lead Systems

Two, three or four binding posts on the bulb terminal heads, or cables issuing from the outlet, of the various forms of bulbs, always interest the student, often puzzle the prospective purchaser; and the different methods of which they are the visible embodiment give rise to interesting discussions pro and con. The choice should depend upon the precision desired, the distance from bulb to instrument, the working range and other requirements of each application. The following is a brief and excellent exposition of the subject from *Bureau of Standards Technologic Paper No. 170:*

If only two lead wires are carried from the thermometer coil to the indicator, the resistance measured is the sum of the resistance of the coil, the platinum or gold lead wires to the head of the thermometer,* and the copper lead wires

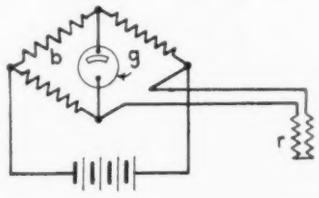


Fig. 3. The fundamental Wheatstone bridge circuit of the resistance thermometer. (P. A. Borden)

from this point to the indicator. The resistance of the platinum or gold lead wires will depend upon the form of temperature gradient along the thermometer from the bulb to the head and upon the depth of immersion. Hence this variable resistance is introduced into the temperature measurement, and changes in the resistance of the lead wires will be interpreted as changes in the temperature of the thermometer coil. There are three general methods for minimizing or eliminating the effect of variation in lead resistance.

1. *Use of a Coil of High Resistance*—The resistance of the lead wires from the coil to the thermometer head and the variation in resistance of the copper lead wires are small compared to a 50-ohm platinum coil. Hence such variations in resistance as are likely to occur do not introduce serious error. Thus, only two lead wires are necessary, from the thermometer to the indicating instrument.

2. *Compensating Lead Wires of the Callendar or Siemens Form*—Both of these methods of compensation are applicable to measurements made with the Wheatstone bridge. The Callendar form of compensation requires four lead wires. Two of the lead wires joined to the end of the coil are connected in one arm of the bridge, and the other two lead wires, which are "dummy" leads formed of a single loop of wire extending to the top of the coil, are connected in the corresponding arm of the bridge. The two sets of lead wires are alike, so that variations in temperature affect each set similarly. The Siemens method of compensation requires three leads and is more often employed industrially in this country.

3. *Potential Terminals*—The use of potential terminals is necessary when the resistance of the thermometer is made very low or when the precision required is such as to make variations in difference of lead resistances inadmissable.

4. Measuring Systems

The measurement of the temperature to which a resistance thermometer bulb is exposed is simply a matter of measuring its resistance. Electrically, a number of methods are possible. Practically, owing to the need of some system of lead compensation and in order to have the temperature indicated on a convenient instrument, the methods are limited to a few. The ultimate instruments are usually of

*In Bureau terminology "thermometer" refers to what is commonly called resistance element or "bulb."

standard forms applicable to other purposes than resistance thermometry. On the other hand, the measuring systems, or methods, of which these instruments constitute the last element, are, in modern practice, especially worked out for resistance thermometry.

The simplest possible method, involving no lead compensation, is the familiar Wheatstone bridge, with the bulb resistor connected to the instrument by two conductors, the resistance of which is added to that of the measuring resistor. Fig. 3 is from an A.I.E.E. paper* to which readers interested in various types of industrial electrical measurements are referred.

For descriptions of the standard circuits, the National Bureau of Standards is again quoted:

1. *Three-Lead Wheatstone Bridge Method*—Fig. 4 illustrates the wiring diagram for a simple Wheatstone bridge and thermometer with the Siemens three-lead compensation. The platinum or gold lead wires $C'd$ and $T'e$ in the thermometer are constructed of as nearly the same resistance

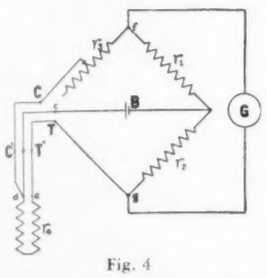


Fig. 4

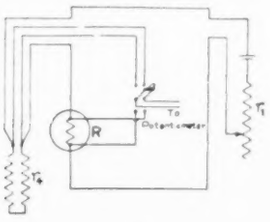


Fig. 5

Lead Systems for Electrical Resistance Thermometers
(Reproduced from Bureau of Standards Technologic Paper No. 170)

as possible and the copper lead wires CC' and TT' must also be of equal resistance. The battery B is connected between the ratio arms r_1 and r_2 of the bridge and to the compensation lead wire cd. A sensitive galvanometer G is connected to the points f and g, as illustrated. By changing r_3 the bridge is balanced until the galvanometer shows zero deflection. Whence from the principle of the balanced Wheatstone bridge we obtain the following relation:

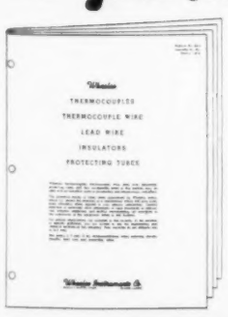
$$\frac{r_3 + C'd}{r_1} = \frac{r_4 + T'e}{r}$$

If r_1 is constructed equal to r_2 then since $Cd = Te$, $r_3 = r_4$. Hence the measured resistance is independent of the resistance of the lead wires.

2. *Four-Lead Potentiometric Method*—Fig. 5 illustrates the wiring diagram for a four-lead thermometer used with a potentiometer. The current, adjusted to a suitable value by the rheostat r_1, flows through a resistance standard R and the thermometer coil r_4. The potential drops across R and r_4 are measured by the potentiometer. Whence from Ohm's law, $e/R = e'/r_4$ where e and e' are the potential

*P. A. Borden, Electrical Measurements of Physical Values. *Transactions A.I.E.E.*, Vol., 44, 1925, pages 238-262.

Do You Know . . .



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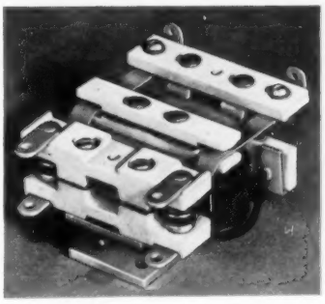

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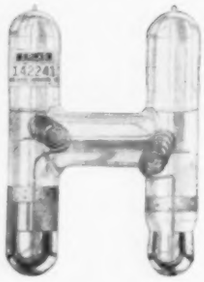

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drops across R and r_4 respectively. Thus, knowing e, e', and R, the coil resistance r_4 is readily obtained. The resistance R may be made adjustable, so that by varying R until $e = e'$ the dial setting gives directly the value of $r_4 = R$. This method is useful in precise laboratory work.

3. *Deflection-Galvanometer Method*—The bridge methods so far described require the adjustment of the bridge until the galvanometer shows zero deflection. The temperature is then read from the setting of the dial or slide wire. It is possible, however, to use an unbalanced bridge with all resistances fixed, except that of the thermometer, which depends upon its temperature, and the temperature is obtained from the scale reading of the galvanometer. Fig 6 shows the wiring diagram for an unbalanced Wheatstone bridge. With the switch S thrown to the right we have the simple Wheatstone bridge, except that the resistances r_1, r_2 and r_3 are fixed. At a certain temperature of the thermometer—for example, 10°C.—its resistance is such that the bridge is balanced and $r_3/r_1 = r_4/r_2$. If the temperature of the thermometer increases, its resistance increases and the bridge is no longer balanced. Thus a current flows through the galvanometer, producing a deflection. In general, the deflection of the galvanometer depends upon two factors—the temperature of the thermometer and the current flowing from the battery B. This current is adjusted to a definite value in the following manner. The switch S is thrown to the left, thus replacing the thermometer by a fixed resistance of such magnitude that suitable value of the current from B deflects the galvanometer to its full scale deflection or to a normal point marked on the scale. The resistance R is adjusted until the galvanometer deflects the proper amount. The switch is then thrown to the right, and, since the factor of variable battery e. m. f. or current is eliminated by this preliminary setting, the scale of the galvanometer may be empirically graduated to read directly the temperature of the thermometer. Thus no further adjustments are necessary as long as this current remains at the proper value, and any temperature is readily observed without the necessity for balancing required in the ordinary bridge. It is possible to have two or more temperature scales on the galvanometer. When two scales are provided —as, for example, 0° to 300°C. and 300° to 700°C.—one of the arms of the bridge is made adjustable to either of two resistances, one giving zero deflection for a thermometer temperature of 0°C. and the other zero deflection for a temperature of 300° C.

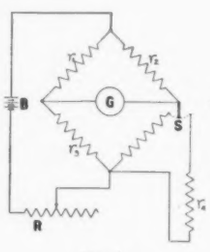

Fig. 6.

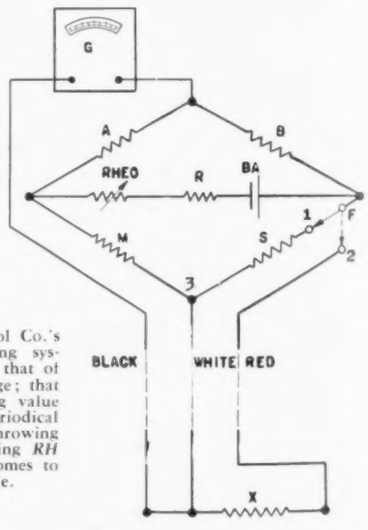

Fig. 7. Circuit of The Bristol Co.'s three-wire, deflection-indicating system. Resistance of M equals that of X at top of temperature range; that of S equals minimum-reading value of X. A and B are equal. Periodical standardizing is effected by throwing switch F to "1" and adjusting RH until galvanometer pointer comes to point "S" marked on its scale.

It seems fairly well established that for industrial applications the three-lead system with balanced Wheatstone bridge possesses the greatest adaptability, in addition to its obvious advantages as a measuring system. Nevertheless, the actual design and construction, and resultant characteristics, of commercially available instruments and accessories are factors of importance. There are recognized *grades* of resistors, as well as various ohmic values. Some

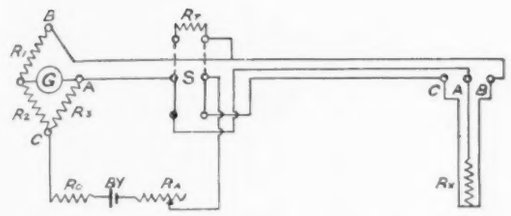

Fig. 8. Circuit of the Thwing-Albert Instrument Co.'s three-wire, deflection-indicating system. K_1, K_2, K_3, are three fixed resistors. K_T is a fixed resistance used for testing calibration of instrument. K_C is a fixed and K_A a variable calibrating resistance for compensating variations in battery emf.

standard resistors are made up in individual coils, each in a thermostated oil bath: they are replicas of the international standards. There are laboratory bridges, and there are inexpensive portable sets designed for rough field service.

Types of Indicating Instruments. Industrial resistance thermometers may be classified by their forms, etc. (see Chapter II) but electrically they are all bridges; thus there are three types of equipment:

(1) "Unbalanced" Bridges: Deflection Methods.—While the unbalanced bridge is usually condemned in electrical laboratory practice, it must be remembered that industrial temperature ranges are relatively short—which means an exceptionally short *resistance*-measuring range and nullifies most objections. Many instruments of this type are on the market. Those designed for industrial temperature measurements—and sold with a choice of primary elements and other accessories—represent specialized research and development; hence should be considered trustworthy.

(2) Null Method, Manually Balanced.—Most of these are the conventional table models, which are further subdivided into plug-out, decade dial switching, slide-wire, and combination. There have appeared also (a) portable outfits for industrial—rather than commercial—services; (b) switchboard models requiring no batteries and approximating the self-balancing instruments in other ways.

(3) Null Method, Automatically Balanced.—These are slide wire bridges, designed for permanent installation, in which the galvanometer commands a servo-motor-driven mechanism which restores balance and at the same time re-positions the indicating element.

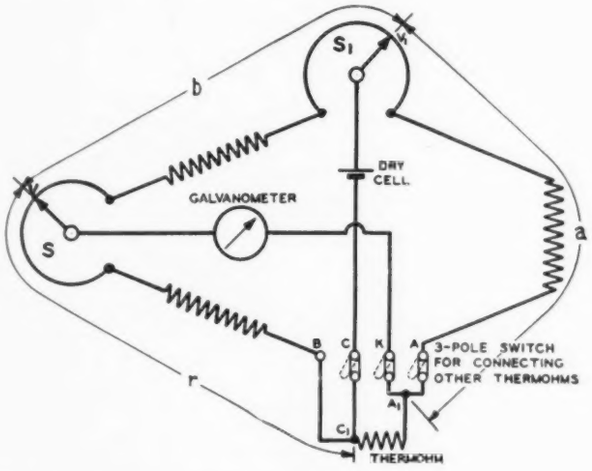

Fig. 9. Circuit of the Leeds & Northrup three-wire, null-method, manually-balanced bridge. Resistors S_1 and S_2 with sliding (potential-point) contacts, are mounted on one disk. Resistance values are such that ratio a/b is always unity. Disk is rotated to make galvanometer read zero; thus balance is established between r and "Thermohm," and temperature is read from scale rotating with disk.

Recorders. The parallel development of self-balancing bridges and potentiometers for industrial service has made available dual-function electro-mechanical assemblies which, considered as recording instruments, are practically identical whether for service as bridges or as potentiometers. They will be described under pyrometers in the next chapter.

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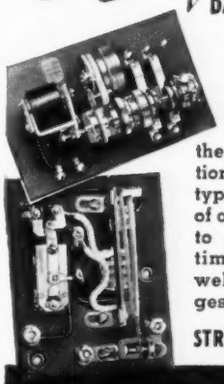

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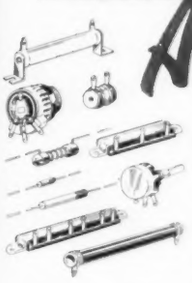

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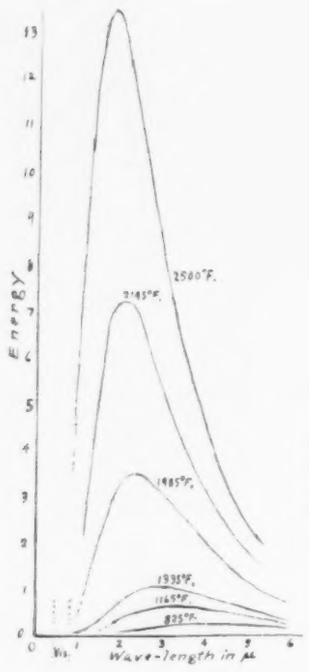
Foundations of Temperature Measurement

(Concluded from page 236)

At high temperatures where metals are vapors, every element sends out (or cuts off) a jagged hill made up of a series of vertical lines, like a business-conditions chart.

The behavior of the continuous-spectrum hill broadcast by a perfect black body has two distinct properties. In the first place, if we draw the hill with a uniform scale of wave-lengths for zero elevation, we notice that the crest of the hill is never in the center of the spectrum, but always over toward the short waves. The short-wave slope of the hill is sharp, the other slope gentle—so gentle that although the spectrum may extend to relatively long waves the elevation



1800
HERSCHEL

1858
STEWART

1859
KIRCHHOFF

1879
STEFAN

1884
BOLTZMANN

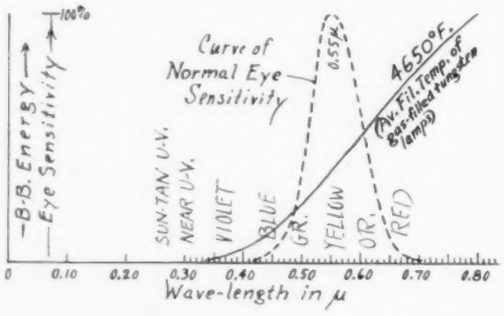
1896
WIEN

1900
PLANCK

YESTERDAY AND TODAY

Abbott, Angell, Barbrow, Benford, Birge, Brickwedde, Brown, Buckingham, Burgess, Cady, Caldwell, Chéveneau, Coblentz, Cohn, Day, Dellinger, Dushman, Einstein, Eppley, Fabry, Fairchild, Féry, Fleury, Foote, Forsythe, Foster, Gibson, Guth, Haas, Harrison, Hefner, Henning, Hoffmann, Holborn, Hoover, Hyde, Kohn, Kurlbaum, Langmuir, LeChâtelier, Leeds, Lewis, Lummer, Mendenhall, Miething, Morse, Moser, Nerst, Nichols, Northrup, Nutting, Paschen, Peters, Pfund, Pirani, Priest, Pringsheim, Ribaud, Richtmyer, Roeser, Rosa, Russell, Schofield, Sosman, Stephens, Suits, Thwing, Waidner, Wanner, Wensel, Worthing, Zwicker.

AND OTHERS!



is so low that we need not draw it when we draw a cross-section of the hill. In the second place, as the temperature of the black body increases, the crest of the hill moves over toward the short wave-lengths. This is true of all ordinary bodies, all of which begin to glow dull red at about 1000° F. We have to say "at about" because the red sensitivity of human eyes varies.

With a further increase in temperature, the body becomes yellow hot, then white hot, and certain stars are "blue hot," meaning that the crest of the hill is in the blue end of the visible spectrum, or even in the ultraviolet.

Thus did the numerous investigators represent by charts and exact figures two distinct effects which had been observed from ancient times, that the brightness of an incandescent body increases with the temperature, and that its color changes with such an increase.

It is important to bear in mind the distinction between these two effects. It is equally important to bear in mind that they are related.

This means that the two problems—of making a brightness pyrometer and of making a color-change pyrometer—must have a common solution.

The perfect solution would be one equation defining the infinite series of contours of the hill, from where it is a low gentle mound in the infrared, to where it is a high mountain with a needle-like peak in the ultraviolet. Long before the nineties, mathematicians were supposed to be able to write the equation of a line-drawing of a human face. The equation of one hill was an elementary exercise for amateurs; the equation of the growth of a hill shouldn't be a difficult trick.

But the equation had to fit the known facts, one of which was that the sectional area of the hill varied as the fourth power of the absolute temperature. That's why we need not remember the names of the early surveyors and must remember Wilhelm Wien.

It was Wien who first gave a two-fold answer—not the final answer but one which first permitted calibrating optical pyrometers for a relatively short but nevertheless useful range. His answer consists of two harmoniously related equations. One is the Wien Displacement Law which simply states that the product of the absolute temperature and the peak energy is a constant. The other is the Wien Distribution Law which plots the contours of the hills—not perfectly but accurately enough for the combination of: (1) wave-lengths which are visible and (2) temperatures which prevail in furnaces. (Wien's law doesn't fit the facts for large values of temperature × wave-length.) The first part of that equation gives the height of the crest of the hill: this maximum varies as the *fifth power* of the absolute temperature! (No wonder brightness increases twenty times faster than temperature at "white-hot" temperatures!) The second part defines the shape of the hill. Neither part can be used alone because wave-length appears in both, but it's the first part that's in mind when references are made to the Brightness Law or the Fifth Power Law.

* * *

Now for some real excitement.

In 1896, the announcement of the Wien distribution law and the discussions of its shortcomings started a race for the honor of formulating a law that fitted the facts at all temperatures and at all wave lengths. Lord Rayleigh (né J. W. Strutt) first forged to the front; then Sir James Jeans took the lead; then at the turn of the century it began to look like a tie between these two; and the world-wide spectators, thrilled by the English racers, failed for several years to see that a German starter was coming closer to the finish-line. And no wonder! This new runner, Max Planck, was beginning to propose equations based on assumptions so remote from common experience—assumptions so unverifiable, so fantastic, that his nearness to the finish-line could not be measured by the accepted rules.

To see why Planck found it necessary to make these assumptions, we only need to take a quick look at the conduction-convection ideal body and at the radiation ideal body, and observe how different they are.

Carnot's body is an ideal gas. It gave rise to the kinetic theory. Heat turned out to be a statistical effect of the kinetic energy of moving particles. Maxwell's laws, describing the distribution of their velocities and energies, were statistical laws of mathematically perfect precision. The picture of the Carnot-Kelvin ideal body, therefore, was a picture of a swarm of little billiard balls. Each billiard ball, of course, could possess any level of energy at any given time. To assume that an atom's energy could be "1000" or "1001" but could never be "1000.435" would have been ridiculous.

On the other hand the picture of radiation was that of a perfect continuity—like the ancient idea of a liquid before anyone thought of atoms. Not only was the spectrum itself absolutely continuous but the energy-content of any infinitesimal wave-length interval could be anything from zero up. And THEREFORE, the amount of energy sent out, for example, by an individual atom in the sun and absorbed by an individual atom on earth, could be anything from . . . oh, well, from zero up, too. The picture *had* to be so! Good heavens, all of the scientific facts of light and of thermal

radiation showed that the continuous spectrum of an incandescent body is due to each atom being able to vibrate at any frequency! Even the believers in the corpuscular theory believed in this continuity of energy! Rayleigh and all the other competitors *had* to base their formulas on atoms and molecules obeying *proven* laws of oscillations!

"All other competitors but me" said Planck (in more elegant terms). "Of course I'm not saying that atoms disobey the proven oscillation laws, but there's the other picture, the Maxwell atom-velocity-distribution laws, which certainly involve separate atoms and work out beautifully in all ramifications of the kinetic theory of heat. So, gentlemen, I had a hunch that the only way of using *statistical* mathematics on the radiation energy curve was to go the whole way—by assuming that energy, like matter, is made up of separate little bits. Following this hunch that energy is like American currency with no coin smaller than one cent, I went further and assumed that a material oscillator cannot transact business with another vibrator by means of checks made out to fractions of a cent. It may even be that the energy owned by an atom—whether fortune or pittance—can only exist in the form of that same radiation currency, with no unit smaller than the one-cent piece, but I'm still working on that. Meanwhile, this being 1900, an easy year for future pyrometer men to remember, I now announce a radiation law that satisfies the requirements of optical pyrometry. This law holds good for all areas and shapes of the radiation-curve hill, from zero to infinity. Therefore it provides at last a Radiation Scale of Absolute Temperature.

"By the way," concluded Planck (though again not in these words), "I've got a name for my least unit of radiation currency. It's the *quantum*. Plural, *quanta*."

Thus appeared the beginning of the now famous Quantum Theory—a by-product of a German physicist's interest in "that peculiar thing, temperature."

But it was not until much more recently that Planck's distribution law was scientifically derived. This work was performed by Einstein and published in 1916 and 1917. It furnishes at last the explanation of temperature in terms of the interaction of radiation and matter—the description of the phenomena underlying our engineering concept of heat. There is no space here for the Einstein Proof, which cannot conveniently be summarized (except by putting it in the form of an application of the law of mass action, excited atom $\rightleftarrows$ atom + quantum). Suffice it to say that in spite of the terrific rate at which startling discoveries have been made since then—in spite of the bewildering variety of sub-atomic wavicles, in spite of energy being mass and vice-versa—the Wien laws as re-formulated by Planck and certified by A.E. himself stand unshaken: the optical pyrometer is an International Standard, as we shall see on returning from our excursion.

As we get back to the plant we can cast an admiring glance at the modern Galileos and Newtons and Carnots and Kelvins: regular fellows to talk to when you have the pleasure of their company; bridge and chess experts some of them, naturally! But they don't want what they call undue publicity so we dassen't visit them on this excursion.

Now back to our practical jobs. The practical result of this excursion is that it has served as an introduction to:

THE INTERNATIONAL TEMPERATURE SCALE

[The following is taken, by permission of the author, from a paper presented before the Temperature Symposium (American Institute of Physics, 1939) **by H. T. WENSEL,** Chief of Pyrometry Section, National Bureau of Standards.]

The International Temperature scale, unanimously adopted in 1927 by the Seventh General Conference of Weights and Measures (representing 31 nations), is based on a number of fixed points whose location on the Kelvin scale relative to the ice point has been determined by gas thermometers. Part I of the text of the scale, given below, is self-explanatory. A few editorial corrections, not affecting the scale itself, were made in 1933.

DEFINITION OF THE INTERNATIONAL TEMPERATURE SCALE

1. The Thermodynamic Centigrade scale, on which the temperature of melting ice, and the temperature of con-

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densing water vapor, both under the pressure of one standard atmosphere, are numbered 0° and 100°, respectively, is recognized as the fundamental scale to which all temperature measurements should ultimately be referable.

2. The experimental difficulties incident to the practical realization of the thermodynamic scale have made it expedient to adopt for international use a practical scale designated as the International Temperature scale. This scale conforms with the thermodynamic scale as closely as is possible with present knowledge, and is designed to be definite, conveniently and accurately reproducible, and to provide means for uniquely determining any temperature within the range of the scale, thus promoting uniformity in numerical statements of temperature.

3. Temperatures on the international scale will ordinarily be designated as "°C," but may be designated as "°C (Int.)" if desired to emphasize the fact that this scale is being used.

4. The International Temperature scale is based upon a number of fixed and reproducible equilibrium temperatures to which numerical values are assigned, and upon the indications of interpolation instruments calibrated according to a specified procedure at the fixed temperatures.

5. The basic fixed points and the numerical values assigned to them for the pressure of one standard atmosphere are given in the following table, together with formulas which represent the temperature (t_p) as a function of vapor pressure (p) over the range 680 to 780 mm. of mercury.

6. Basic fixed points of the International Temperature scale—

	°C.
(*a*) Temperature of equilibrium between liquid and gaseous oxygen at the pressure of one standard atmosphere (oxygen point)	—182.97
$t_p = t_{760} + 0.0126(p-760) - 0.0000065(p-760)^2$.	
(*b*) Temperature of equilibrium between ice and air-saturated water at normal atmospheric pressure (ice point)	0.000
(*c*) Temperature of equilibrium between liquid water and its vapor at the pressure of one standard atmosphere (steam point)	100.000
$t_p = t_{760} + 0.0367(p-760) - 0.000023(p-760)^2$.	
(*d*) Temperature of equilibrium between liquid sulphur and its vapor at the pressure of one standard atmosphere (sulphur point)	444.60
$t_p = t_{760} + 0.0909(p-760) - 0.000048(p-760)^2$.	
(*e*) Temperature of equilibrium between solid silver and liquid silver at normal atmospheric pressure (silver point)	960.5
(*f*) Temperature of equilibrium between solid gold and liquid gold at normal atmospheric pressure (gold point)	1063

Standard atmospheric pressure is defined as the pressure due to a column of mercury 760 mm. high, having a density of 13.5951 g./cm.^{3}, subject to a gravitational acceleration of 980.665 cm./sec.^{2} and is equal to 1,013,250 dynes/cm.^{2}.

It is an essential feature of a practical scale of temperature that definite numerical values shall be assigned to such fixed points as are chosen. It should be noted, however, that the last decimal place given for *each* of the values in the table is significant only as regards the degree of reproducibility of that fixed point on the International Temperature scale. *It is not to be understood that the values are necessarily known on the Thermodynamic Centigrade scale to the corresponding degree of accuracy.* [Italics MFB's.]

7. The means available for interpolation lead to a division of the scale into four parts.

(*a*) From the ice point to 660°C. the temperature t is deduced from the resistance R_t of a standard platinum resistance thermometer by means of the formula

$$R_t = R_0 (1 + At + Bt^2).$$

The constants R_0, A, and B of this formula are to be determined by calibration at the ice, steam, and sulphur points, respectively.

The purity and physical condition of the platinum of which the thermometer is made should be such that the ratio R_t/R_0 shall not be less than 1.390 for $t = 100°$ and 2.645 for $t = 444.6°$.

(*b*) From —190° to the ice point, the temperature t is deduced from the resistance R_t of a standard platinum resistance thermometer by means of the formula

$$R_t = R_0 [1 + At + Bt^2 + C(t - 100)\, t^3].$$

The constants R_0, A, and B are to be determined as specified above, and the additional constant C is determined by calibration at the oxygen point.

The standard thermometer for use below 0°C. must, in addition, have a ratio R_t/R_0 less than 0.250 for $t = -183°$.

(*c*) From 660°C. to the gold point, the temperature t is deduced from the electromotive force e of a standard platinum *vs.* platinum-rhodium thermocouple, one junction of which is kept at a constant temperature of 0°C. while the other is at the temperature t defined by the formula

$$e = a + bt + ct^2.$$

The constants a, b, and c are to be determined by calibration at the freezing point of antimony, and at the silver and gold points.

(*d*) Above the gold point the temperature t is determined by means of the ratio of the intensity J_2 of monochromatic visible radiation of wave-length λ cm., emitted by a blackbody at the temperature t_2, to the intensity J_1 of radiation of the same wave-length emitted by a blackbody at the gold point, by means of the formula

$$\log_e \frac{J_2}{J_1} = \frac{c_2}{\lambda}\left[\frac{1}{1336} - \frac{1}{(t+273)}\right].$$

The constant c_2 is taken as 1.432 cm. degrees. The equation is valid if $\lambda(t + 273)$ is less than 0.3 cm. degrees.

"The statement that the International scale 'conforms with the thermodynamic (centigrade) scale as closely as is possible with present knowledge' is not entirely true today [states Wensel]. The introduction to the scale stated that the scale 'is to be regarded as susceptible of revision and amendment as improved and more accurate methods of measurement are evolved.' The International Conference, meeting every six years, was scheduled to consider revision of the temperature scale in October 1939, but failed to meet in 1939 on account of the unsettled political conditions. Among the revisions by which the conformity with the thermodynamic scale might be improved are (1) the substitution of Planck's formula

$$\frac{J_{\lambda T_1}}{J_{\lambda T_2}} = \frac{e^{c_2/\lambda T_2} - 1}{e^{c_2/\lambda T_1} - 1}$$

for the form of Wien's formula given in the scale, (2) the use of a slightly higher value for c_2, (3) some modification in values assigned to some of the fixed points to make departures from the thermodynamic scale smaller and more regular, (4) making the junction between the thermocouple and the resistance thermometer ranges at the freezing point of antimony instead of at 660°C., (5) extension of the scale below —190°C., and (6) better specifications for the standard resistance thermometer.

"None of these revisions, with the exception of (4) and (5), would make the scale more useful. Its greatest usefulness lies in the fact that its universal use has practically eliminated ambiguities in the specification of temperatures. If and when the scale is modified, the resulting differences will be known and conversion from the 1927 scale to the modified scale can be easily made. If for some time during and after such a modification, people are careful to state on which scale temperatures are being specified, no confusion should occur. The first requirement of any scale is that it provide means by which any thermal state may be unambiguously specified." [End of quotation from Wensel's paper.]

Front-cover photo story:

New Research Building for Cummins Engine Co.

Increased demand for diesel engines finds the Cummins Engine Co. occupying new research and development headquarters at Columbus, Indiana, intended to provide the finest testing facilities in the diesel industry. One entire side of the building is devoted to engine testing facilities. Six 10x21-ft. test rooms are arranged in pairs, with observation corridors between pairs, as the photograph shows. Each corridor is equipped with dynamometers and other instruments compactly arranged at the sides and above double-glazed observation windows. One operator can oversee tests on two engines at once. Instrumentation at each position includes a tachometer, revolution counter, recording thermometers, supercharged pressure gages, water pressure gages for front and rear of block and cylinder head, fuel and lube oil pressure gages, water intake vacuum gages, and meters for air intake of supercharged engines and fuel consumption.

A multi-point Leeds & Northrup potentiometer permits taking temperature readings at various points on the engine. A General Radio Strobotac is used to study spring action, etc. By means of an automatic weigher-feeder, all lube oil used is weighed to 1 oz. while the engine is running.

Chemical and metallurgical laboratories have been provided for close and continuous control over all of materials used in engine production, and to check experimental work. The met lab has a completely equipped darkroom; a 200,000-lb. Baldwin-Southwark universal; a 100-inch-pound Tinius Olsen impact tester for small c.i. and steel samples; Monotron, Rockwell and Brinell hardness testers; a Hevi-Duty electric lab furnace; and a Bausch & Lomb research micrographic outfit. Don J. Cummins supervises research and development. Details were worked out by Austin Co. engineers with the two Cumminses and A. F. Loertz, plant engineer.

The American Society for Measurement and Control
1117 Wolfendale Street, Pittsburgh, Pa.
Phone Fairfax 0161

The September Open Meeting of the A.S.M.&C. will be held MONDAY EVENING, SEPTEMBER 23, at 7:45 o'clock, at the Bureau of Mines Auditorium, 4800 Forbes Street.

It is a pleasure to announce that Mr. FORD R. LAMB, Executive Secretary of The American Society of Tool Engineers will fly from Detroit especially to address our meeting.

Mr. Lamb is one of the three or four men in this country who combine facilities for obtaining exact knowledge of employment conditions for skilled personnel, together with knowing how to present his facts.

His subject—naturally—will be "The Acute Shortage of Skilled Help, and Just What It Means to You."

Non-members are cordially invited.

R. J. S. PIGOTT, President — FRANK C. McGOUGH, Secretary

Chicago Society for Measurement and Control
(Formerly Chicago Instrument Society)
2626 West 31st Boulevard, Chicago
Phone Canal 4100

O. T. Lay, Meteorologist at the U. S. Weather Bureau at Chicago will give a talk, **'Back of the Weather,"** at the October dinner-meeting, Thursday evening, **October Third,** at the Central Y. M. C. A. auditorium, 19 S. LaSalle Street.

Dinner at **6:30** sharp.

Those unable to attend the dinner are cordially invited to hear Dr. Lay's talk at **7:45.**

Earl C. Rieger, *Chairman*, International Harvester Co.
Walter W. Kagi, Western Electric Co.
R. N. Powell, Wisconsin Steel Co.
J. S. Bogen, Universal Oil Products Co.
J. P. Dahlberg, Youngstown Sheet & Tube Co.
W. Brock, Socony Vacuum Oil Co.
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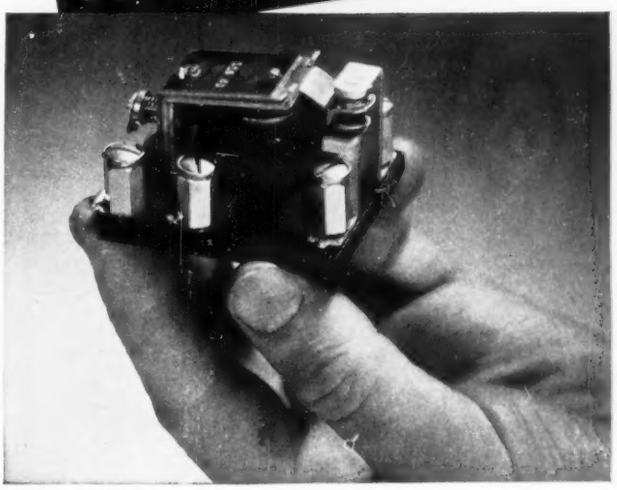

The design of the new Ward Leonard Little Giant Single Pole Relay is simplicity itself. It is sturdily built yet there is not an ounce of material in it that is not essential to efficient performance. Measures only 1⅞"x2⅝". Controls ¾ H.P. on 115-230 volts. Ideal for heaters, pumps, compressors, signal lights, etc. Described in Bulletin 105.

WL Relay Bulletins

Little Giant Relays	Bulletin 105
Midget Relays	" 106
Intermediate Duty Relays	" 81
Heavy Duty Relays	" 131 & 132
Sensitive Relays	" 251
Time Delay Relays	" 351 & 362

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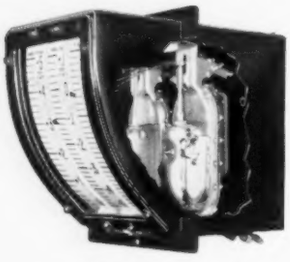
Multi-Pointer Gages for indicating drafts, pressures, differentials are available with any number of pointers from one to twelve. They are actuated by sturdy yet sensitive diaphragm units.



Multi-Pointer Gage

Flow Meters. For indicating, recording and integrating the flow of steam, feed water, compressed air and other fluids.

Coal Meter

Granular Material Meters For accurately measuring the flow of coal or other granular materials in gravity chutes from overhead bunkers. The total quantity of granular material is shown on a large illuminated counter which may be easily read at a distance of 50 feet.

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Complete Information on any of the above Bailey products will be gladly furnished upon request.

G-14

BAILEY METER COMPANY

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THE MONTH'S NEW INSTRUMENTS

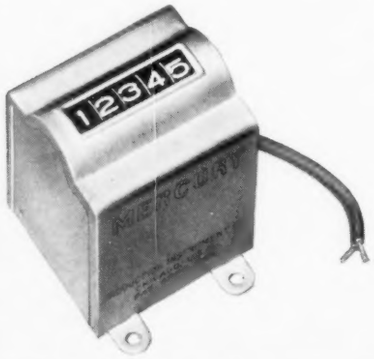
In this department we strive to report each month ALL the new devices for measurement, inspection, testing, metering and automatic control—in the form of concise technical descriptions. When writing to manufacturers directly, please mention this department as your source of information. Or write to Information Section, Instruments Publishing Company.

Resistance Decades

New series of Resistance Decades contain 10 non-inductive resistors mounted on a high grade ceramic insulated rotary selector switch. This assembly in turn is mounted on an engraved Bakelite panel and the whole is enclosed in a cast aluminum box. These Resistance Decades are available in increments from 1/10th ohm to 1,000,000 ohms.—*Shallcross Mfg. Co., 10 Jackson Ave., Collingdale, Pa.*

Electric Counter

New "Mercury" counter has energy requirement of about 2 watts at rated voltage. All units are tested at 600 counts per minute. Five number wheels register to 99,999 and repeat. Units are available for any 60-cycle a-c. voltage up to 230, any d-c. voltage to 115.—*Production Instrument Co., 702 W. Jackson Blvd., Chicago, Ill.*



Thermometers for Micro Testing

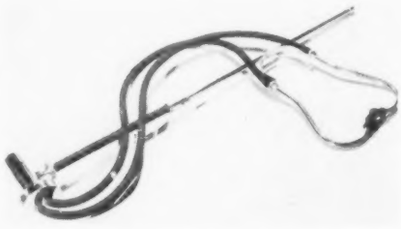
Specially developed for temperature measurements on small samples, new enclosed-scale chemical thermometers have a bulb less than 1/16" diam. and approx. 8" long; but readings are said to be obtainable in 3 seconds. Available singly or in sets of three (0-100°C., 100-200°C. and 200-300°C. or equivalent F. scales). Enclosed scale is of porcelain, with the split-tens style of numerals assuring maximum legibility for available width.—*Walter H. Kessler Co., 213 Pearl St., New York City.*

Beckmann Thermometer

A radically new construction of the Beckmann type thermometer is announced. It is said to be such that "rattling" of tubing in case is eliminated. Simplification and sturdy construction make new instrument suitable for manipulation by inexperienced laboratory assistants, it is said, while the customary Beckmann least-division is retained. —*Walter H. Kessler Co., 213 Pearl St., New York City.*

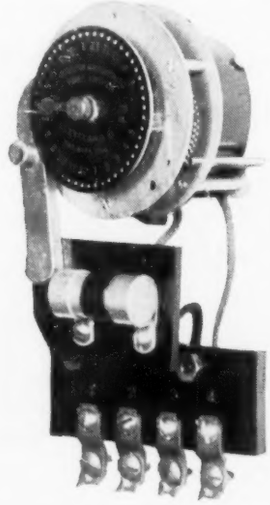
Industrial Stethoscope

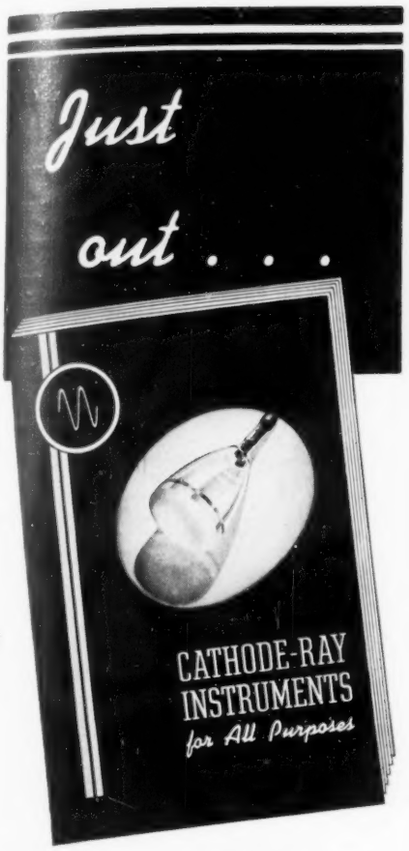
New listening device, designated "Test-A-Tone," though non electric, is provided with a volume control, operated by a thumbscrew, thereby permitting acoustic examinations of a wide variety. Applications include engines, turbines, pipe line leaks, etc. —*Test-A-Tone Co., 274 Madison Ave., New York City.*



Automatic Timer

New model of maker's automatic timer employs a self-starting and "self-oiling" electric clock movement; and mercury-to-mercury contacts housed in unbreakable metal-clad tubes. There is only one moving operating part; and there are no springs. Timing dials in hours, minutes and seconds. —*Emra D. Bacon, 4513 Brooklyn Ave., Cleveland, Ohio.*





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★ Among the many new items found in this spiral-bound catalog is the new Type 208 Cathode-Ray Oscillograph which, announced in these pages only two months ago, has already indicated that it will revolutionize all future designs for this class of equipment. Also the Type 213-A Cathode-Ray Modulation Monitor, a recent addition to the DuMont line, which we assure you will more than "earn its salt" wherever a radio transmitter must operate at peak efficiency. Many other DuMont instruments, tubes and television equipment are also included.

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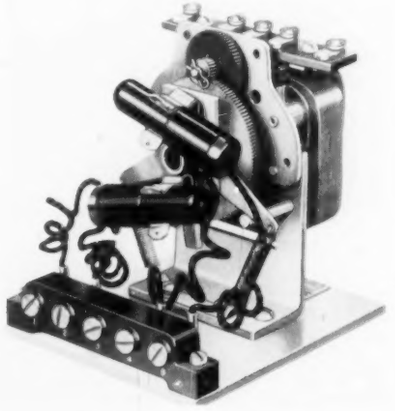
Process Timing Mechanism for Recorder-controllers

Exact duration of batch processing, in addition to automatic temperature or pressure control, is provided by new Process Timing Mechanism for "Fulscope" Record-

ing Controllers. Being all-electric, timing mechanism is as positive as electrical current available at user's establishment. Timing process is manually started by adjusting instrument for desired time period. With new feature, timing automatically starts, not immediately, but when the apparatus reaches the set point of the controller. (Length of time required for this set point to be reached makes no difference in the operation of the new timing mechanism.) At end of desired period, mechanism automatically terminates the process. To facilitate timing successive batches of the same duration, a "stop" is furnished: when set at the desired timing period, the pointer can be quickly spun to the "stop" and the starting operation speeded up.—*Taylor Instrument Companies, Rochester, N. Y.*

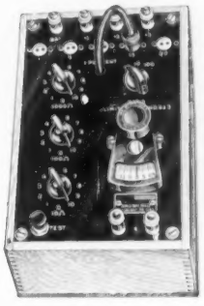
"Motorelay"

New "Motorelay" consists of a small reversible geared-head shaded-pole Barcol Motor which tilts two mercury tubes. Tubes are arranged to give s-p, d-t, operation,



with spring return to a neutral "off" position. Use of "Motorelay" permits throttling, floating, or proportioning control of a 5-amp. load from an instrument having a current rating as low as 0.35 amp. Chattering is said to be eliminated because a momentary contact at instrument is not sufficient to close the mercury tube switch. New device is said to be particularly suited to floating or proportioning control of line voltage motors operating large dampers, large valves, speed adjusters, voltage regulators, etc.—*Barber-Colman Co., Rockford, Ill.*

623
Limit Bridge



THE new No. 623 Shallcross Limit Bridge is a Wheatstone Bridge arranged for production resistance testing and incorporates a built-in standard. It provides a simple, rapid, and accurate tool for the inspection of resistors for manufacturers of Radio Resistors, Telephone Equipment, and many other phases of electrical industry. Requires no technical knowledge to operate and is arranged for various degrees of accuracy and has automatic change of voltage.

Write for Bulletin No. 2488-HQ

SHALLCROSS MFG. CO.
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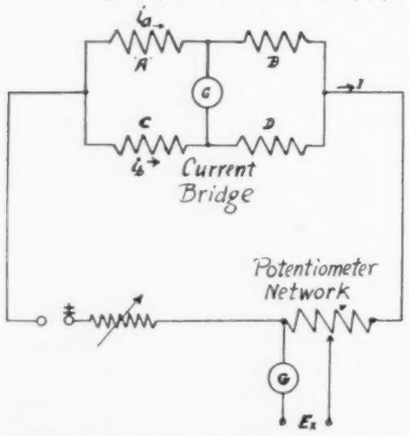
A New A-c. Standard Measurement Method

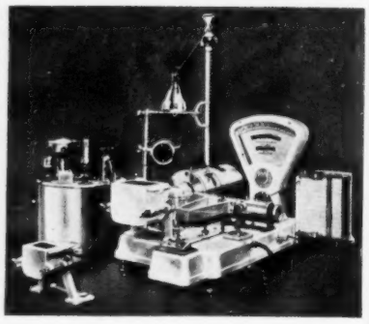
Alternating current measurements at commercial frequencies have to date been made by dynamometer type instruments, calibrated on d-c. and then used as transfer or secondary instruments. These instruments are subject to the limits of deflection measurements. The ideal a-c. standard is one which has the following characteristics: —(1) Null method, subject to accurate determination; (2) Null condition to be based upon some basic physical property of a stable element, or elements, rather than upon chemical action, heat measurement, etc.; (3) The null indication must be independent of temperature of instrument; or the influence must be small and accurately known; (4) The frequency of the measured current, over a wide range, must be eliminated as influencing factor. By definition, "One ampere alternating current is that alternating current which will produce the same heating effect as one ampere direct current." The calorimeter and U Tube methods have been the most prominent methods of standardizing. Both are clumsy and subject to instrumental and personal errors. Over a wide temperature range the temperature coefficients of resistivity of most metals and alloys are as stable as any of the physical properties accurately measurable. If a carefully prepared metal resistor is made one of the arms of a Wheatstone Bridge (*A*) and the other arms, *B*, *C*



and *D* are made from materials having a negligible temperature coefficient of resistivity, the bridge will balance, i.e. $AD = CB$, only when resistor *A* is at some temperature *T*. Let us assume the ambient temperature of the bridge to be 0°C. A certain amount of energy, supplied by i_a, will be required to bring *A* to the temperature *T* at which its resistance will be the value necessary to balance the equation. If the instrument temperature is *t*, greater than 0°C., the energy necessary to maintain *A* at the temperature *T* will be less than in the former case and the current through *A* when the bridge balances will be less than the former current i_a. Since the bridge resistances remain constant when the bridge is balanced, the voltage drop across the bridge will decrease with an increase of ambient temperature, causing a corresponding decrease of current i_b through arms *C* and *D*. This effect and the above-described effect are additive in producing a change in the bridge current *I* which is inversely related to the temperature of the bridge. To compensate for this effect of ambient temperature, arm *B* is also made from a material having a temperature coefficient of resistivity. However, *B* is so designed that the current in it has a negligible effect upon its resistance (temperature). Then, as the ambient temperature increases, the quantity *CB* increases and for the bridge to balance the resistor *A* must rise to a new value, higher than *T* in the first example. It has been found that by selecting the respective arms of the bridge with the proper temperature coefficients of resistivity and the proper resistance ratios, a bridge may be designed and built which will have either of the following characteristics:—(1) The bridge will balance only when a predetermined total bridge current *I* has been established, and this current may be made independent of the ambient temperature. (2) The bridge, when balanced, will indicate a total current *I* through the bridge which may, by design, be made to vary directly or inversely with the ambient temperature. Condition (1) is that for which we were seeking. By using properly-designed non-inductive resistors, the bridge may be calibrated on d.c. and then used as a current standard for alternating currents over a wide frequency range. Condition (2) is useful where it is desired to compensate for some other factor which varies with ambient temperature. An a-c. standard built as described is highly stable but is limited to the indication of one fixed current value. Such standards are valuable for occasional checking but lack the desired flexibility. This is readily overcome by placing one of the current bridge units in series with a calibrated potentiometer network. This forms a potentiometer identical in operation to the familiar type of instrument, and one which may be used either as a d-c. or as an a-c. instrument.

When comparing two alternating voltages, account must be taken of their wave shapes and phase relations. The wave-form problem may be eliminated by using a common source of power; the phase problem has been defeated by the use of a new type of galvanometer. The first experimental instruments built, several years ago, have held their calibration through severe tests. The resistor arm *A* has been designed to work at a temperature well below the point of visible radiation. It is, in most cases, vacuum-mounted. The resistor itself is a carefully prepared wire, welded to the terminals. Except in the case of extreme precision units the time required for the resistor to reach equilibrium is negligible. This new standard will be available in commercial form in October 1940.—*Hurl E. Adams, Yellow Springs, Ohio.*

PLASTOGRAPH



Recording Plastometer—based on the dynamometer principle and practically "weighing" the plasticity of the different materials. Measures consistency over a wide range of materials—from fairly viscous, syrupy substances to unvulcanized rubber. Has been applied successfully in RESEARCH as well as in PLANT CONTROL (for continuous operation) in the following industries:

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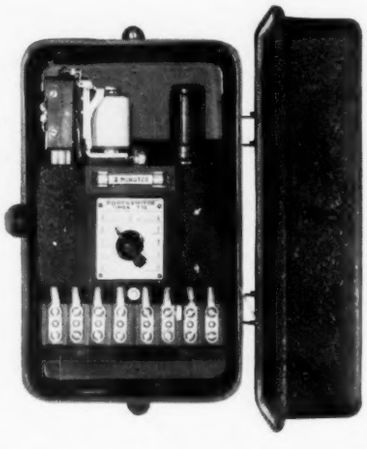
Short-interval Timer

New "Electronic Timer Type T15" is a universal interval timer, for ranges from 1/20th second to two minutes. Control is accomplished through a specially designed



snap-action relay of 1,000-watt capacity. Equipment is flexible with reference to actuating control, permitting both momentary push button and sustaining contacts control. It is universal for six timing ranges represented by timing valves snapped into a readily-accessible clip. Timer has been designed to permit complete interchangeability of equipment. Thus, machine process calibrations for one timer apply to all. It is claimed also that unit has been designed throughout for an unlimited life guaranteed to match that of any machine to which it is applied.—*Photoswitch Inc., 21 Chestnut St., Cambridge, Mass.*

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continuous measurement of specific gravity

Utilizes a basically new principle of liquid density measurement by which the specific gravity of liquids may be instantly and continuously determined by immersion during the actual conditions of processing. Also may be used in closed tanks, vats and pipe lines, etc., while fluid is subjected to moderate heat, pressure, flow and agitation. Reads varying density in open tanks by immersion from surface to 50 foot depth. Wired for attachment to standard recorders and automatic density control equipment.

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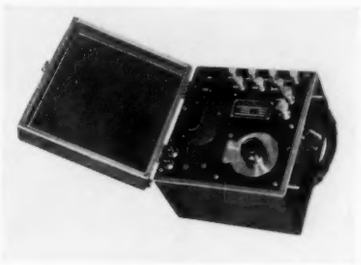
Knopp Load Analyzer

Knopp Load Analyzer is a portable instrument especially designed for quickly making power factor and related measurements on individual loads (such as fluorescent lighting equipment and neon signs). New Analyzer, because of its multirange feature, permits measurement of power factor, watts, and volts on loads of a few watts up to as high as 24,000—48,000 watts, depending upon the voltage range. It accomplishes the measurement of power factor, watts, and volts in an entirely new and unique manner which offers following features: (1) Power factor read directly by turning a knob; (2) Watts and volts quickly read by means of same measuring element; (3) No indicating pointers or delicate movements. Knopp Analyzer is available in five different models with eight current ranges from 0.5 to 100 amps and potential ranges from 120 to 480 volts. Power factor measurements can be made from 10% lag to 85% lead. Wattages from 10 to 48,000 watts are read from a proportional linear scale by observing a unique stroboscopic disk.—*Electrical Facilities Inc., 4224 Holden St., Oakland, Calif.*



Combination Set and Tube Tester

"Model 803 Portable Service Shop" combines functions of set tester and tube tester. Dimensions 12¼" × 13" × 6", weight 12¼ lbs. Space is provided for test leads and small tools. Set tester functions include measurement ranges of 0-10/50/500/1000 for d-c. voltages (at 1000 ohms-per-volt) and for a.c. and output voltages. D-c.: 0-1/10/100/1000 milliamperes and 0-10 amperes. Ohmmeter ranges 0-500/5000/1 meg./10 megs. Decibel ranges—8 to 15, 15 to 29, 29 to 49 and 32 to 55. A self-contained battery serves for the medium ohms range and a built-in power supply for the others. Provision is made for testing all old and new tubes. "Dynoptimum" circuit is utilized and filament voltages are available up to full line voltage. All tests are at standard RMA plate voltages and loads and include hot inter-element short and leakage tests for individual elements, individual section tests for multi-purpose tubes, etc. A built-in mechanical roll chart lists test data for all tubes.—*Radio City Products Co., Inc., 88 Park Place, New York City.*

MAINTAINING PROPER DRAFT is relatively a simple job once a Hays Draft Gage has been installed. Accurate measurements supplant guesswork, resulting in more efficient combustion.

HAYS ORIGINATED and perfected the dry or diaphragm type of draft gage and today Hays Draft Gages are standard equipment in thousands of the nation's boiler rooms.

HAYS DRAFT GAGES are offered in a wide variety of types from the V-type, illustrated above, to recording gage. Send for our catalog today. Write to 925 Eighth Avenue, Michigan City, Indiana.

The HAYS CORPORATION
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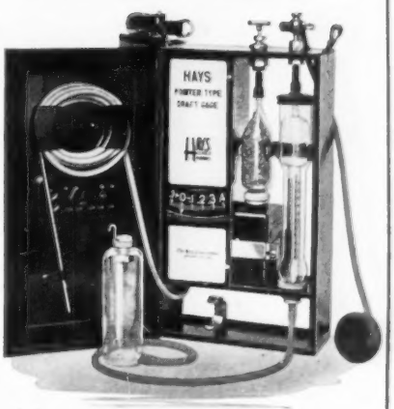
A LABORATORY JOB DONE IN THE FIELD



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rheostat until pointed comes to check line on scale. Release push-button and read temperature. Instrument continues to follow temperature without further adjustment. Where instrument is permanently installed, standardizing to check line should be done once a day. Resistance bulb illustrated is intended for use in pipes, ducts, etc. Length of tube below head from 1½" minimum to 18". Standard head is threaded for ½" pipe opening. Other sizes and types available. Thermometers placed 25 feet or less from bulb use two connecting wires. All others have three-wire systems, permitting variation in length, temperature, and gauge of copper wire. Scale ranges are drawn to customer's requirements, with 50°F. minimum total span. "Model 72-RT" has 6" scale. Smaller models include 3⅛", 2⅜", and 1⅜" lengths. Double-range instruments are available on special order. "Model 72-RT" is housed in cast aluminum case 7⅝" × 6½" × 2¼", for switchboard, wall-mounting, or portable use. Battery inside or outside the case is optional.—*J-B-T Instruments, Inc., 441 Chapel St., New Haven, Conn.*

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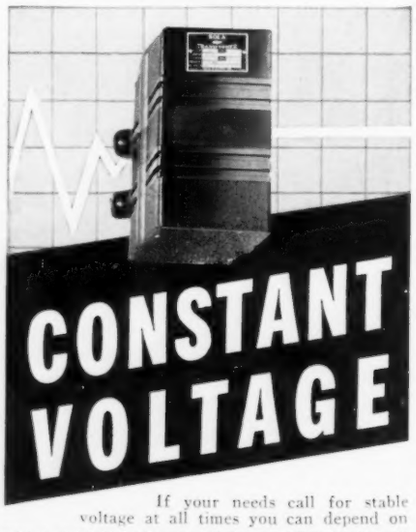

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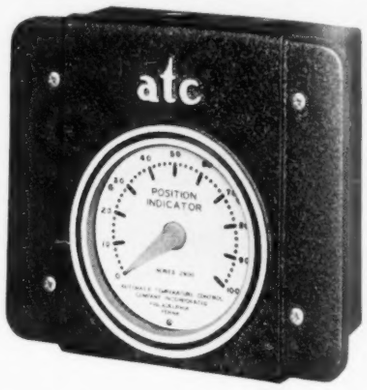

eter-relay developed for the purpose. Several standard models of the transmitter are available. One is for service where the motion to be indicated can be directly connected without intermediate gearing. Another has a 315° stroke. Other types are based on the same operating mechanism except that intermediate gears, built into the transmitter, provide for other ranges in stroke.

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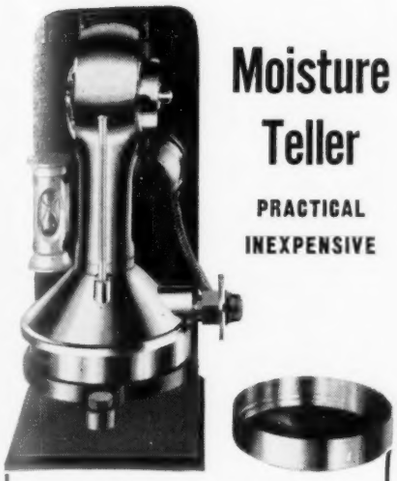

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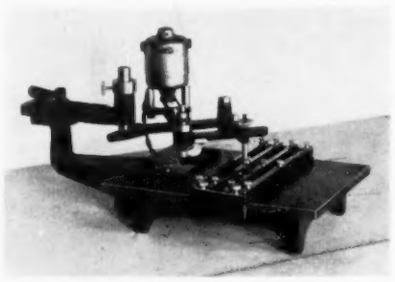

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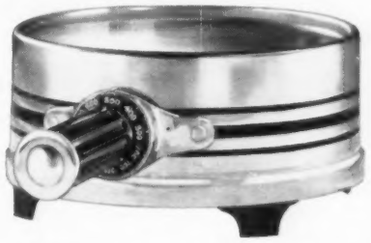
With new "Type AK-1" hook-on volt-ammeter, alternating current can be read instantaneously on both insulated and non-insulated conductors by hooking the instrument around the line. For voltage readings, connect two leads (furnished with instrument) and then flip the thumb-manipulated selector switch to the desired voltage position on the scale. Designed for use on conductors of 2″ max. diam, new volt-ammeter weighs 3½ pounds, is designed for one-hand operation. Four current ranges, 0-15/60/150/600 amps, and two voltage ranges, 0-150/600 volts are available at the setting of a six-position snap switch. Accuracy is within 3 per cent. An integral part of the instrument is a C-shaped, split-core current transformer designed to be operated without a trigger. To make measurements, transformer is pulled open and placed against the conductor. A slight push on the handle snaps the transformer shut. The measurement completed, a gentle pull springs open the dovetail joint of the transformer and releases the conductor. The dovetail joint is said to assure that particles of dirt which would cause large errors in ordinary butt joint have almost negligible effects on indication. Indicating instrument used is marker's "Type DO-40" miniature rectified instrument. Readings are taken on a single, uniformly-divided scale approx. 2½″ long, marked in red and black figures corresponding to figures on selector switch. Handle, molded as part of the Textolite case, provides insulation and safety for operator, has a slot for a carrying strap.—*General Electric Co., Schenectady, N. Y.*

Laboratory Hot-plate

New electric hot plate identified as "Handi-Plate," measures 4½″ diam. and 2″ high. 750-watt capacity, with thermostatic control, and dial reference markings from 100-700, in intervals of 100. Surface temperature range is between 100 and 550°R. Three different models are offered for 110 volts a.c.: hot plate only; hot plate with support rod clamp attached; hot plate on a heavy cast iron support base with rear extension including a ⅜″ by 20″ stainless steel support rod.—*Precision Scientific Co., 1758 North Springfield Ave., Chicago, Ill.*



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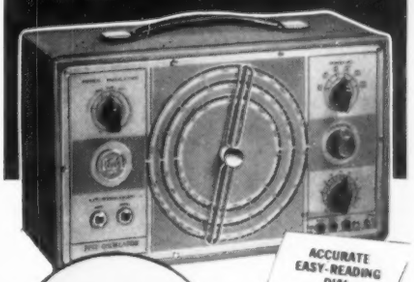

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Engine Safety Cutout

New "P607A" safety device is designed to protect stationary internal-combustion engines by interrupting their operation if lubricating oil pressure drops hazardously low

or if cooling water temperature rises too high. It is said to be particularly essential on engines that operate for long periods of time unattended. Two models are available: P607A with manual reset, and P607B without manual reset. Latter is designed for use on motors with automatic starting equipment where a means is provided to shunt the circuit around the P607B until motor starts and oil pressure rises to normal. A feature is universal application:—For engines with a distributor type of ignition, device is wired to break circuit on temperature rise or pressure fall. For engines with a magneto type of ignition the opposite terminals are used which short-circuits primary of spark coil to ground. For Diesel engines, device is set up to control a solenoid valve in fuel line to injection system. That there is no manual reset latch (to keep reset button depressed while motor is being started) is an added safety feature. Reason: if motor is started and oil pressure does not build up, motor will stop as soon as operator takes his finger off reset button. 4 × ½" bulb is inserted in any ½" pipe tapping in the block, a special packing gland being furnished. S-p. d-t. mercury switch. Overall dimensions, 6⅛" high, 5⅛" wide, 2¼" deep.—*Minneapolis-Honeywell Regulator Co., 2950 Fourth Avenue South, Minneapolis, Minn.*

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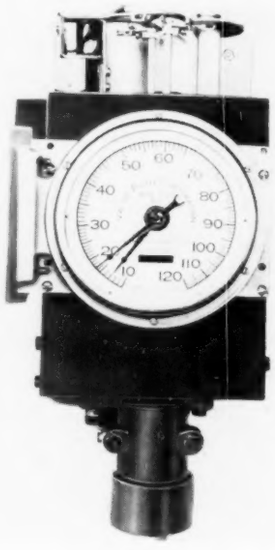
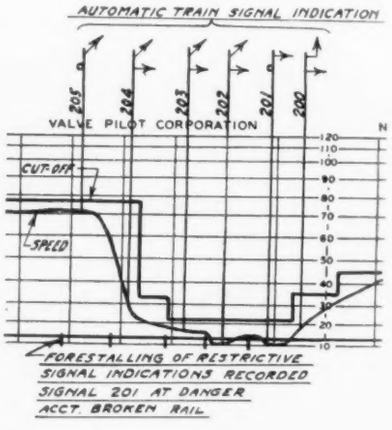


proceeds in accordance with the operating rules dictated by that signal. New "Automatic Train Signal Recorder" records each time this forestalling operation takes place. The same tape chart records speed and cut-off (steam admission to the cylinders) con-



trol indicated and recorded by maker's "Loco Valve Pilot" instrument, with which this ATS Recorder is housed. Management thus has a graph of where restrictive signals occurred by examining the forestalling lines on the tape. The speed curve shows how the engineman regulated his speed in accordance with each signal. Operation of Automatic Train Signal Recorder is controlled by an electro-pneumatic switch in the forestalling circuit of the train control mechanism, switch being closed by admission of air to warning whistle in cab at moment of forestalling. When switch is closed, current energizes an electro-magnet and causes a pencil to make a short mark at right angles to time axis. Except when forestalling occurs, pencil draws a straight line near edge of tape. It is claimed that for the first time there is obtained from one instrument a record of the engineman's attention to three important railroad operating factors—efficiency, speed, and safety.—*Valve Pilot Corporation, 230 Park Ave., New York City.*

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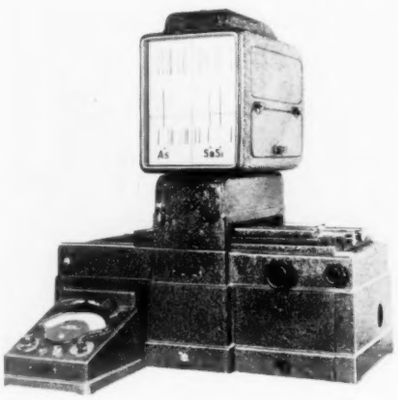
A new Comparator-Densitometer by Applied Research Laboratories is designed for accurately and speedily projecting a spectrogram on a viewing screen; and enabling positive spectral lines identification of up to 70 elements. Pressing a control button starts automatic motor scanning. Density of selected spectral line is read from the scale of an indicating instrument in terms of percentage of light transmission. With this unit, it is claimed, spectograms may be correctly interpreted for qualitative and accurately read for quantitative spectrochemical analysis. Among characteristics of new apparatus are: (1) no special foundation required; (2) qualitative and quantitative analysis combined; (3) positive identification of stray element lines; (4) saves time; complete spectrogram study and measurements made at one station; (5) obviates need of marking plates; (6) no long warm-up period; (7) scattered light error eliminated; (8) personal error minimized by motor scanning; (9) projects magnified view of $\frac{5}{8}'' \times \frac{5}{8}''$ section of spectrogram being measured; (10) spectral lines permanently in focus with slit of densitometer; no focusing required; densitometer slit easily aligned with spectral lines; (11) variation in transmission of plates compensated for by adjusting knob; (12) manual scanning beside motor scanning is available. Density range of new automatic apparatus feature is from 0 to 2.—*Harry W. Dietert Co., 9340 Roselawn Ave., Detroit, Mich.*



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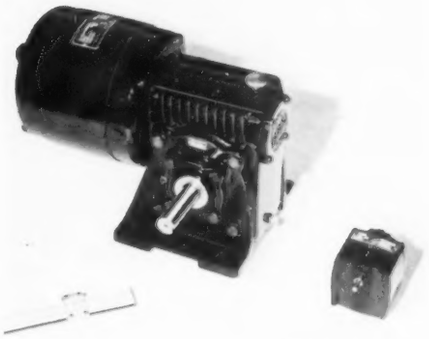

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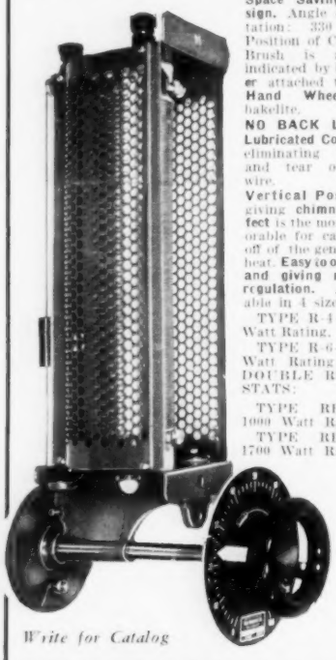

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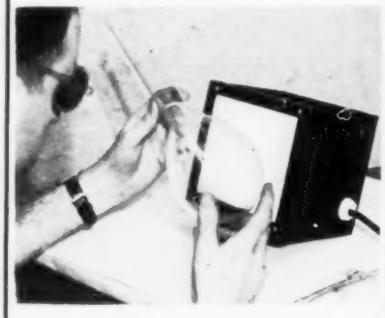

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Physics for Technical Students. Vol. I — Mechanics and Heat. Vol. II — Sound, Electricity and Magnetism, Light. By WILLIAM BALLANTYNE ANDERSON. McGraw-Hill Book Co., New York, 1937. Cloth, 6¼ × 9¼ inches. Vol. I, viii + 378 pages; Vol. II, x + 436 pages. Price (each vol.) $2.50.

These two volumes are excellent texts in undergraduate physics, not only for the technical students for whom they were written, but also for non-technical students who may be interested in the practical applications of the fundamental principles of physics. These texts assume that the student has had only the mathematics included in college algebra and a small amount of trigonometry. The material is covered in a clear, concise manner and will be easily understood by students with the required preparation.

One of the outstanding features is the copious use of illustrative problems. At the end of each chapter a paragraph has been included, "Review of Vital Facts," Both of these features should be of great service to the student in his preparation. The many practical applications which have been listed in the texts will help to stimulate interest. The chapter on meteorology is particularly good. To the reviewer it seems that the material covered in heat and thermodynamics is much less than it should be. This is probably the weakest part of the whole treatment. Many schools of engineering will find that the lack of mathematics in the text is a definite handicap. It would seem that engineering students should be prepared and should profit by a greater use of mathematics.

—EMERSON M. PUGH, *Associate Professor of Physics, Carnegie Institute of Technology, Pittsburgh.*

Physik für Studierende an Technische Hochschulen und Universitaten. By PAUL WESSEL. Ernst Reinhardt Verlag, München, 1939. (Author's address: 33 Dicconson St., Wigan, Lancashire, England.) Cloth, 5 × 8¼ inches, xii + 550 pages. Price 3.90 RM.

This book is intended as a first survey of the field of physics, but it differs widely from the elementary textbooks that are known to the reviewer. On the one hand, the scope of the book is wide: It contains a large number of applications and, in addition, the results of the most modern research, such as quantum mechanics, atomic disintegration, television, etc. On the other hand, it is strictly dogmatic and descriptive. Even in the most elementary fields, like mechanics of mass points, the author gives definitions and laws but does not give theoretical connections between these definitions and laws. The reviewer fears that this book will not help the reader to obtain an understanding of physical facts and processes. However, it certainly will be quite useful for memorizing the laws of physics, or as *a reference book*. Especially for this latter purpose, the unique typographical arrangement, the large number of excellent illustrations, and the extensive collection of tables of formulas and numerical constants, as well as a comprehensive index, will prove to be extremely helpful. A large number of examples are included in the text, and a long list of examination questions and answers is given as an appendix.

—I. ESTERMANN, *Associate Professor of Physics, Carnegie Institute of Technology, Pittsburgh.*

The Microscope. By R. M. ALLEN. D. Van Nostrand Co., Inc., New York, 1940. Cloth, 6 × 9¼ inches, viii + 286 pages. Price $3.

This book fills a real need, as it is devoted to the theory and manipulation of the microscope. The book treats the subject in the simplest possible manner, omitting all but essential formulæ.

The book is a practical thesis on the microscope for those who are interested in microscopy. For those interested in special fields the author has listed a number of specialized volumes in a bibliography. A large number of books are included and the reviewer notes only one omission—*The Microscope, Its Construction, Use and Care* (published by the Spencer Lens Co. in 1935). The list would have been slightly more valuable if all books listed had their publication dates listed: at present about half of the dates are given.

The author is well qualified to prepare this book: he has lectured and written on this subject for years. In 1931, he gave a series of lectures before the American Foundrymen's Association, which after revision, appeared in 1939 as "The Microscope in Elementary Cast Iron Metallurgy" (reviewed in the May 1940 *Instruments*).

—RICHARD RIMBACH

Electrical Measurements—Second Edition. By FRANK A. LAWS. McGraw-Hill Book Co., Inc., New York, 1938. Cloth, 6¼ × 9¼ inches, xiv + 739 pages. Price $6.

In less than a generation after the first edition of this classic came out in 1917, "Look it up in Laws" became a saying oft-heard wherever electrical measurements or testing were being made. More and more frequently was it heard and heeded—or heeded without being spoken—until 90% or more of all copies of this best-selling technical textbook were dog-eared—those of older printings almost falling apart. Professor Laws had designed his text for electrical engineering students, but he had done such a masterly job that in recent years an electrical testing laboratory—whether large or small, whether in Maine or in California—would be considered incomplete if his book was not there. Thus, before he died, Professor Laws had the supreme satisfaction that comes from seeing one's contribution to learning universally recognized, but instead of resting on his laurels he worked for years to perfect his *magnum opus*. The preface to this second edition is signed by M. I. T. Professors Bennett and Hoadley, who modestly undervalue their own work and declare that the revised text is "essentially" as Professor Laws left it.

—M. F. BEHAR.

Physical Science in Modern Life. By E. G. RICHARDSON. D. Van Nostrand Co., Inc., New York, 1939. Cloth, 5 × 7¾ inches, 256 pages. Price $3.

Note that "modern" qualifies "life"—not "physics." Some aspects of modern science, but little of modern physics, will be found in this extraordinary—this delightfully "different"—book. To the best of our recollection, the author doesn't ever allude to protons, photons, relativistic effects or quantum phenomena.

And you'll search the book in vain for mathematical symbols other than 12345678 90. Beg pardon: the author *does* make use of the decimal point!

So that when we tell you that his first chapter is on Streams and Eddies, and his second chapter is on Vibrations and Waves, you may say to yourself that the first without Prandtl's differential equations, and the second without reference to de Broglie's theory of matter and radiation, might be good enough for elementary-school or trade-school boys but not for you.

Well, sir, if that's what you're saying to yourself, you're mistaken—and you're in for a pleasant surprise when you read these chapters, as well as for a real treat when you read the others. For this book is obviously a *tour de force* by an author of high scholarship and exquisite refinement who deliberately and with impishness aforethought addresses his intellectual equals in words intelligible to a schoolgirl. (Yes, Dr.

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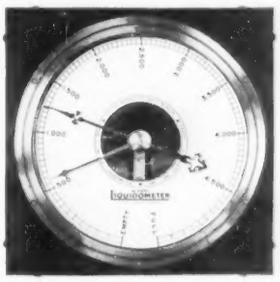

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Richardson, you've written your collection of essays in conversational style, ostensibly for Mr. and Mrs. Public and their kids, and they'll eat it up, or ought to, but in your heart you've been striving to hold the interest of research workers, engineers, science teachers and other cognoscenti . . . and you've succeeded.)

From the modest Preface: " . . . those recent advances . . . which make contact with our everyday existence. . . . My only justification of the subjects chosen—some momentous, some trivial—is that they have been the things that have interested me. If you have wondered how an aeroplane flies—what constitutes a quicksand—why it is usually necessary to shake an embrocation, but not a mayonnaise—how a man can glide for four hours in an engineless craft—what limits clarity on the television screen and power in broadcasting stations—how a fish swims—shall we have trips to the moon; these are some of the subjects on which I intend to discourse. An aunt of mine . . ."

The twelve charming essays called "chapters" range from aerodynamics in the first, and resonance in the second, through supersonics, colloids, thermal conductivimetry, clouds, gliding, infra-red photography, Kerr cells, "talkies," radiography, subjective phenomena, nervous reactions, locomotion, speech and dialects, to interplanetary rocket-ship possibilities. (These are not the printed titles.) The technically-educated reader will find two or three chapters mere "refreshers" but—unless he has an exceptionally broad scientific education—he will find most of them full of unfamiliar information.

Of the sixty illustrations, more than half appear to be heretofore-unpublished photographs, obtained mostly from famous research laboratories and presumably taken especially for Dr. Richardson.

The only flaws to which this reviewer desires to point are those slips that creep into the manuscripts of highly-cultivated (and self-confident?) writers and are not caught by the awe-struck editorial assistants at publishers' offices. "Providing" instead of "provided that" or simply "if" (page 103) is bad enough, but "a third alternative" (page 97) and "micro" defined as "thousandth" or written for "milli" (page 133) are to be deplored in such a superbly prepared work.

—M. F. BEHAR

M.K.S. Units and Dimensions and a Proposed M.K.O.S. System. By G. E. M JAUNCEY and A. S. LANGSDORF. Macmillan Co., New York, 1940. Pressboard, 5½ × 8½ inches, viii + 62 pages. Price $1.

In the Foreword the authors say: "The purposes of this little book are: to acquaint electrical engineers, physicists, and teachers and students of electrical engineering and physics with the properties of the new meter - kilogram - second (M.K.S.) system of basic units; to describe methods for changing from one set of basic units to another; to give reasons for the adoption of the ohm as the fourth basic unit (a question left open by the I.E.C. in 1935); to describe a proposed M.K.O.S. system of basic units; and to discuss the difference between magnetic flux density (B) and magnetic field strength (H)."

For the first two of these purposes the book is admirable and timely. It is brief and well written, which should insure its being widely read. It points out the numerous advantages of the M.K.S. system clearly and forcefully. There is a crying need for more good physics texts which use the M.K.S. system throughout.

The last three purposes mentioned in the Foreword amount to the championing of controversial issues concerning each of which the authors have presented one side. There are several fallacies in the authors' arguments for the necessity of choosing a fourth basic unit. Their choice of the international ohm is a mistake, since the International Committee on Weights and Measures recommended that all electrical units be established by the so-called absolute measurements. This action is equivalent to giving the permeability of free space a fixed value. This change in the methods used in establishing our electric and magnetic units was to have gone into effect on January 1, 1940, but has been delayed because some national laboratories have not completed their measurements. When these methods are established there will be no place for a standard ohm, but rather the ohm will be established by laboratory measurements such as have been made at the National Bureau of Standards. The ohm established in this way is certainly more unchangeable than any laboratory standard could be, and it is believed from past experience that the changes in such a standard ohm are greater than the inaccuracies in establishing the ohm by absolute measurements.

The question of dimensions is not as closely tied up with standards as the authors imply. It has been pointed out by Bridgman, Birge and others that dimensions for dimensional analysis may be chosen quite arbitrarily. The number of primary quantities (mass, length, time, etc.) used in dimensional analysis does depend upon the system of equations employed and upon certain assumptions regarding factors of proportionality. The authors' use of four primary quantities in the M.K.S. system is proper and desirable but not necessary. A perfectly consistent system can be set up with the three primary quantities, meter, kilogram, and second.

The authors try to show that B and H are fundamentally different and therefore must have different dimensions. Even if we grant this premise, we need not accept the conclusion. There are several examples of fundamentally different quantities having the same dimensions, such as work and torque; or Young's Modulus, shear modulus of elasticity, and pressure. In the Gaussian and Heaviside-Lorentz systems B and H do have the same dimensions. For many pur-

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poses it is desirable that B and H have different dimensions, and this is one of the advantages of the M.K.S. system. A fourth primary quantity fits into it naturally. A fourth primary quantity must be used to distinguish dimensionally between B and H, and the use of this fourth primary quantity effects several other desirable distinctions. The ohm which the authors propose for this purpose has no advantage over the ampere, volt, or coulomb. A definite choice is not necessary. One can choose whichever one wishes for the particular problem at hand, just as in some mechanics problems it is desirable to choose force in place of mass in dimensional analysis.

The authors' choice of the non-rationalized system is unfortunate. The report of the committee of the American Association of Physics Teachers studying this problem states, "The question of rationalization of M.K.S. units has been left open by international committees. Opinion seems to be rather evenly divided on the subject, with perhaps a majority of those who have studied the matter carefully in favor of rationalization. It seems to this committee that it is not so important which way the matter is decided, but that it is important to have it decided one way or the other at this time. It would be unfortunate to have two forms of the M.K.S. system come into use. We have, therefore, listed definitions only for the rationalized units." Three excellent texts (*Matters, Motion and Electricity* by Smyth and Ufford; *Principles of Electric and Magnetic Measurements* by Vigoureux and Webb; *Principles of Electricity and Electromagnetism* by Harnwell) are now on the market using rationalized M.K.S. units. A choice has been made. We should stick to it.

With the non-rationalized system new names would have to be chosen for magnetomotive force, magnetic field strength, electric displacement, and some other quantities. As the authors say, rationalizing eliminates the 4π in some equations but introduces it into others. However, rationalization does eliminate the 4π from the equations which are most used.

This book is well worth reading, but it should be read critically.

— EMERSON M. PUGH, *Associate Professor of Physics, Carnegie Institute of Technology, Pittsburgh.*

Pressure Gauges, Indicators, Thermometers, Pyrometers. By JAMES SMITH. Chemical Publishing Co., New York, 1939. Cloth, $4\frac{3}{4} \times 7\frac{1}{2}$ inches, 144 pages. Price $1.50.

"Printed in Great Britain" is all that appears on the left-hand page backing the title-page. We had looked there for the usual copyright notice, being curious to know the vintage of the original text. (Our guess is nineteen-eleven.)

But that's only one side of the picture. This pocket-size book—reprint of an old one or not—is worth every cent of its moderate price, as a "starter" for young or inexperienced instrument men, as a supplemental general reference for students and even as one of the books that should be on a handy shelf in a plant instrument department.

"A Handbook for the Practical Man and the Student" is the truthful sub-title. "B.Sc., A.M.I.Mech.E." appears under the name of the author—who no doubt compiled this handy little volume for students in those excellent "Mechanics' Institutes" which for generations have enriched the British Empire with skilled, self-reliant, self-starting mechanical engineers only a rung below Mechanical Engineers.

Barometers, pressure and vacuum gages and engine indicators are dealt with in two-thirds of the book; thermometers and pyrometers in the last 42 pages. The emphasis, of course, is on boiler-room practice. Although the instruments shown are old, their types are not obsolete and the common-sense text is ever-new.

—M. F. BEHAR.

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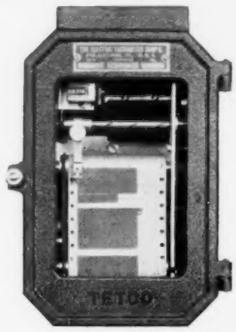

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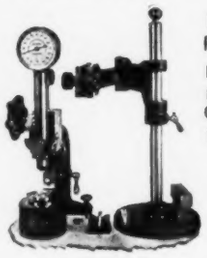

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